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DESIGN OF A MOBILE COMBUSTION DIAGNOSTIC FIXTURE (MCDF)

Didier Devynck

November 1984

US ARMY BALLISTIC RESEARCH LABORATORY
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A Mobile Combustion Diagnostic Fixture (MCDF) has been designed. This fixture is intended to be used in connection with chemical diagnostic techniques in order to provide data on the phenomena involved in the ignition process of the propelling charge in a gun. Special care has been taken of the safety of operation of the fixture.

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I. INTRODUCTION

The development in the past decade of such two-dimensional, two-phase flow, interior ballistic models as TDNOVA[1] has provided a substantial improvement of theoretical gun performance predictions and significant guidelines to charge designers. Quite surprisingly though, this modeling effort has not been accompanied by parallel studies to improve the ignition and combustion submodels, and as a result, theoretical studies using such models are performed using a simple surface-temperature ignition criterion followed by a single, global energy release at the propellant surface described by the standard $r=ap^n$ burning law. As the models become more sophisticated and the igniter-charge interactions more complex, such a description is no longer realistic.

Indeed, some experiments conducted with the Ballistic Research Laboratory 155-mm Howitzer simulator[2] have shown that, under certain circumstances (weak igniter, low temperature, etc.), the early part of the ignition process is significantly different from what can be expected:[2,3] acoustic oscillations of a small luminous front are observed in the radial ullage between the charge and the chamber during the combustion of the basepad. Then a very strong luminosity appears at the forward end of the chamber before any substantial burning of the base region of the charge proper. This phenomenon has been attributed to gas-phase combustion of products pyrolized from the igniter and propellant early in the cycle.

To support this assumption, it is necessary to obtain data on the chemical species produced during the early stage of the ignition. Numerous chemical analysis techniques are available to provide the required results. Among others, gas chromatography and optical methods, such as laser excited fluorescence or laser Raman spectroscopy, have proved to be very useful in providing this kind of information (mass spectrometry is also a widely used technique, but since it is not operational at the Ballistic Research Laboratory, it will not be talked about in the following sections of this report).

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[1] P. S. Gough, "Modeling of Rigidized Gun Propelling Charges," Ballistic Research Laboratory Contract Report No. ARBRL-CR-00518, November 1983, AD# A135860.

[2] T. C. Minor, "Characterization of Ignition Systems for Bagged Artillery Charges," 17th JANNAF Combustion Meeting, CPIA Publication 329, Vol. II, pp. 45-67, November 1980.

[3] T. C. Minor, "Experimental Studies of Multidimensional Two-Phase Flow Processes in Interior Ballistics," Ballistic Research Laboratory Memorandum Report No. ARBRL-MR-03248, April 1983, AD# A128034.

However, these techniques involve fragile apparatus which cannot be used with a simulator such as that cited above. Chromatographs and spectroscopic equipment are difficult to carry around and could not resist the blast caused by the chamber rupture during firings with the simulator.

All those reasons generate a need for a special fixture which would allow such measurements to be made in a laboratory environment. Therefore, a Mobile Combustion Diagnostic Fixture (MCDF) has been designed, and it is the purpose of this report to present how the design of the MCDF has been conducted.

II. DESIGN REQUIREMENTS OF THE MCDF

The design of the MCDF was guided by the requirements listed below :

1. MCDF must be capable of being carried to, and operated in, the location of measurement apparatus. This implies that MCDF must provide adequate safety factor (10x) to permit operators contact during firing.

2. MCDF must be composed of a combustion chamber and a relief tank.

3. Combustion chamber must operate at pressures up to 5,000 psi.

4. Relief tank must allow the expansion of the gases down to the atmospheric pressure.

5. MCDF must be designed so a rupture disk may be placed between the two chambers.

6. Combustion chamber must be manufactured of a material showing excellent corrosion resistance properties for possible future use with liquid propellants.

7. Temperature conditioning of the combustion chamber must be possible.

8. Pressure transducer(s) must be installed in the combustion chamber.

9. Both combustion and relief chambers must be equipped with three windows, two of which must be aligned on an axis perpendicular to that of the fixture and the third one must have an axis perpendicular to these two axes. Possibility of replacing windows by fiber optics must be available.

10. Relief chamber must be equipped with at least three gas sampling ports.

An assembly drawing is presented in Figure 1 for reference purposes. The detailed design of the MCDF is discussed in the following sections of this report.

A. Combustion Chamber

The value selected for the volume of the combustion chamber is 100 cm^3. This is achieved with a diameter of 40 mm (1.57 in.) and a length of about 80 mm (the final length of the chamber may be slightly different due to other considerations, such as the presence of seals).

The choice of the material has been dictated by both requirements Nos. 3 and 6. The selected alloy must exhibit strength and corrosion resistance. The latter property is typical of nickel-base superalloys. Among these superalloys, the Inconel Alloy 718 can be given very satisfactory mechanical properties by an appropriate heat treatment (see Appendix A).

Because this fixture is to be used in rooms that are not necessarily firing ranges, a very high safety factor has been taken into account in the design of the MCDF: the chamber has been designed for a maximum allowable pressure of 350 MPa (50 kpsi). With this value, as can be seen in Appendix A, the chamber wall thickness should be equal to about 6.35 mm (0.25 in.). However, due to other considerations discussed below, the final wall thickness is nowhere less than half an inch (this would require a pressure of 550 MPa or 80 kpsi for yielding). This should then make the combustion chamber perfectly safe.

The chamber is closed at the rear end by a threaded plug which is equipped with a 607C-type Kistler piezoelectric pressure transducer and the firing electrodes. This firing plug also carries a venting system which is simply a Harwood 4-L dead plug (the use of a valve would result in difficulties in handling the firing plug). This venting system is to be used only in the unlikely case where the rupture disk does not blow during the combustion.

The ground electrode is simply a piece of steel wire tightly fit in a hole on the internal side of the plug. As to the other electrode, which must be electrically isolated, it is identical to that designed by R. E. Tompkins[4] at the Ballistic Research Laboratory. It consists of a small metallic spindle which includes a conical portion (see Figure 2). This conical portion fits into a similarly conical housing machined in an electrode carrier, the external shape of which is exactly that of a 607C-type Kistler gage. This way, only one type of cavity has to be machined in the plug (with the slight difference that, for the pressure gage, the gage is separated from the chamber by a small

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[4] R. E. Tompkins, Personal communication at BRL.

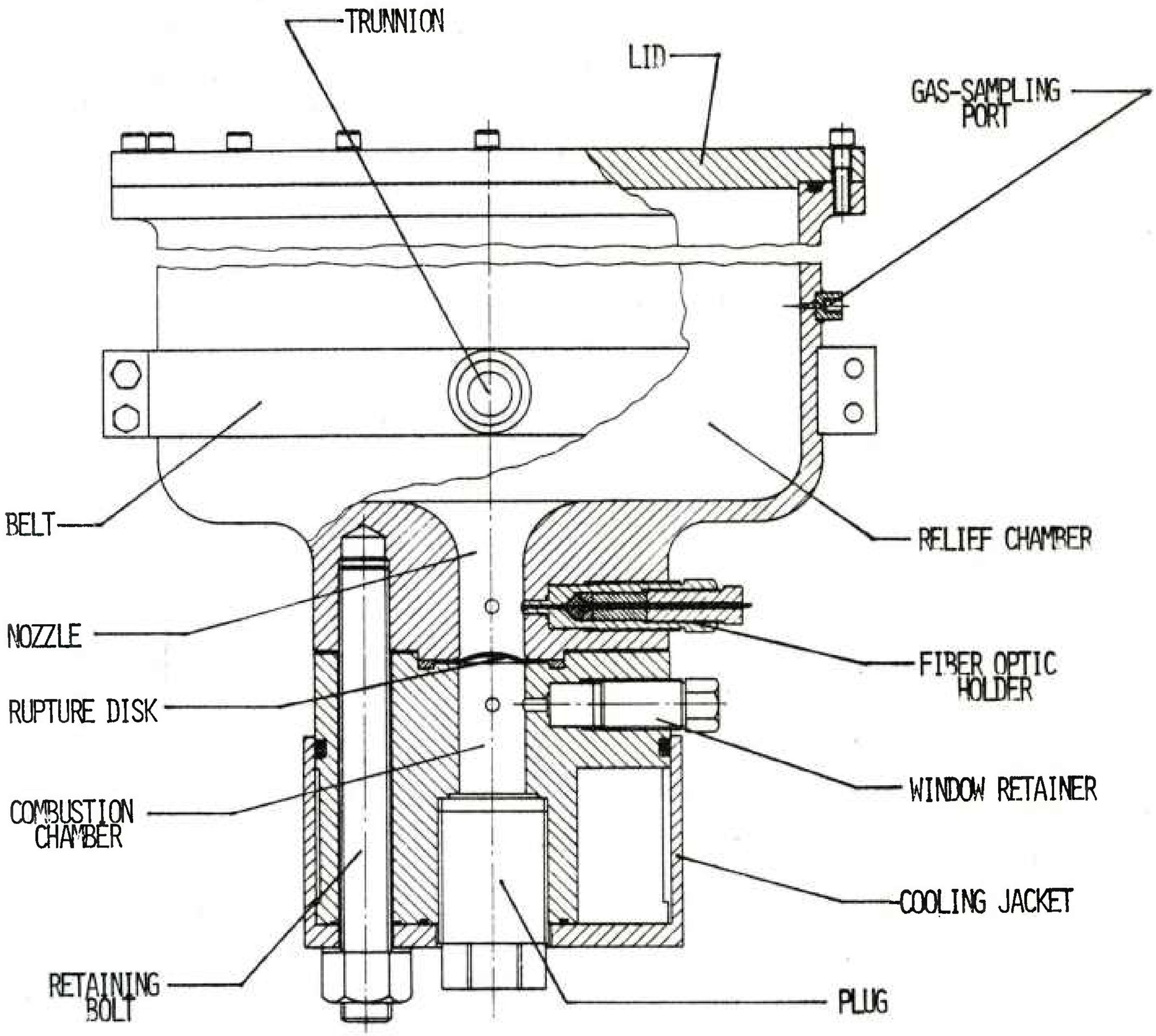

Figure 1. MCDF: Assembly Drawing

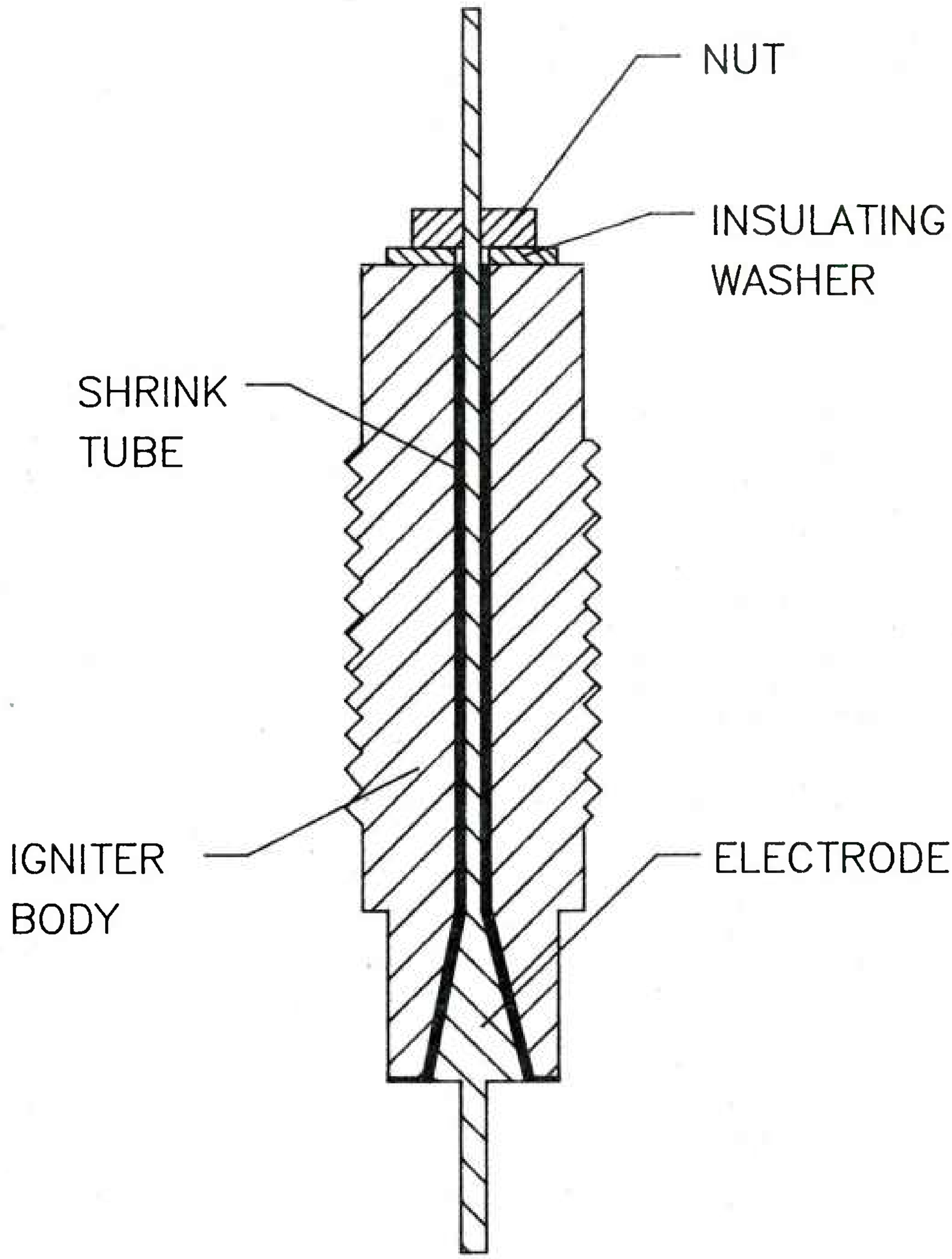

Figure 2. Firing Electrode Mount

diameter channel in order to protect the gage from thermal shocks; in the case of the firing device, the diameter of this channel has to be much larger to avoid any contact between the electrode and the plug). Electrical isolation between the electrode and its housing is accomplished by using a piece of shrink tube around the electrode. The electrode is held in its housing by a nut mating the threaded external end of the electrode (a nylon washer is inserted beneath the nut). Thus the piece of shrink tube also provides the sealing of the firing system when the nut is tightened.

The other end of the chamber is designed so as to make possible the use of a rupture disk. The rupture disk is intended to provide a separation between the combustion chamber and the relief chamber. For reasons that are presented in Appendix B, the selected disk is a Fike* conventional pre-bulged disk, the useable diameter of which is 1.5 in. (this value is then that of the inside diameter of the combustion chamber). According to Fike's mounting configurations, this disk is held between flanges through four 1 1/8 in. bolts equally spaced on a 5 3/4-in. diameter circle. Therefore, the overall chamber outside diameter is equal to 229 mm (9 in.).

With such a large value, it is then easy to machine ports in order to install windows. For its mechanical strength and its optical properties, fused silica has been selected as the window material. It is available in disks of various diameters and thicknesses. The thickness of the disk determines its strength, and a value of 25.4 mm (1 in.) has been chosen (according to the manufacturer specifications, this permits the use of the windows at pressures exceeding 700 MPA or 100 kpsi). The diameter depends upon the size of the laser beam used for the optical measurements. Since the laser beam is focused on the axis of the chamber, its diameter is not constant; the beam shape is such that its diameter is equal to 16 mm (5/8 in.) at the location of the outside wall of the chamber. Therefore, the threaded retainer that holds the window must have a size that allows the machining of the corresponding tapered hole. A 1 1/8-12 thread has then been selected—a value that permits the use of a 25.4-mm (1 in.) diameter window. The diameter of the channel between the chamber and the window has been determined according to the same beam taper and is therefore equal to 7.6 mm (0.3 in.) on a length of 12.7 mm (0.5 in.). These window ports must be machined between the holes that allow the bolts mentioned in the above paragraph to go through the chamber.

Four locations are then available. Since only three windows are required on the MCDF, the location left free is used to

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The use of this product for this project does not constitute an endorsement of this materiel by the U.S. Government.

install a pressure gage. For versatility purposes, the pressure gage is mounted in an adapter that fits a housing identical to the window ports. Therefore, four ports are machined as described above.

Since the window axis is as close to the rupture disk as possible, four scallops may be machined at the rear end of the chamber to be used for temperature conditioning. Like the visualization ports, they are machined between the bolt holes in the chamber wall. A groove connects these scallops to each other, and the fluid used for the conditioning is retained by a jacket that covers the chamber and on which fittings are welded for fluid inlet and outlet. This jacket is held by a total of 16 screws on the rear face of the chamber. Wherever it is necessary, Viton O-rings insure the sealing of the conditioning cavity.

For the chamber itself, i.e. at the plug and at the window ports, the sealing is achieved by using the method illustrated in Figure 3.

Figure 4 presents a drawing of the chamber alone.

B. Other Features

The first function of the relief chamber is to allow the expansion of the combustion gases after the rupture of the disk. The first requirement in the design of the relief chamber is then related to its volume. Since the design pressure of the combustion chamber is 350 MPa (50 kpsi), the expansion factor must be equal to about 350. This leads to a relief chamber volume of 35 liters (approximately 9 gallons). This is achieved with a diameter and a length both equal to 355 mm (14 in.). It should be noted that the gases flow into the relief chamber through a channel, the diameter of which is equal to that of the combustion chamber (Figure 5). This channel is intended to act as a nozzle to smooth the expansion of the gases which might otherwise result in a shock wave.

Moreover, this channel is also used for optical measurements during the expansion of the gases, and visualization ports must be machined in the wall, as well as threaded holes, to mate the bolts used in holding together both chambers and the rupture disk. Therefore, this portion of the relief chamber is but an extension of the combustion chamber, and its inside and outside dimensions must be equal to those of the combustion chamber.

The corrosion resistance requirement is not so strong for the relief chamber as it is for the combustion chamber. However, excessive oxidation of the inside wall should be avoided.
The relief chamber is then made of type 316 stainless steel, which is corrosion resistent but could not be used for the combustion chamber because of mediocre mechanical properties.

The relief chamber must be vacuum-compatible because it may be desired that vacuum be achieved in the chamber before an

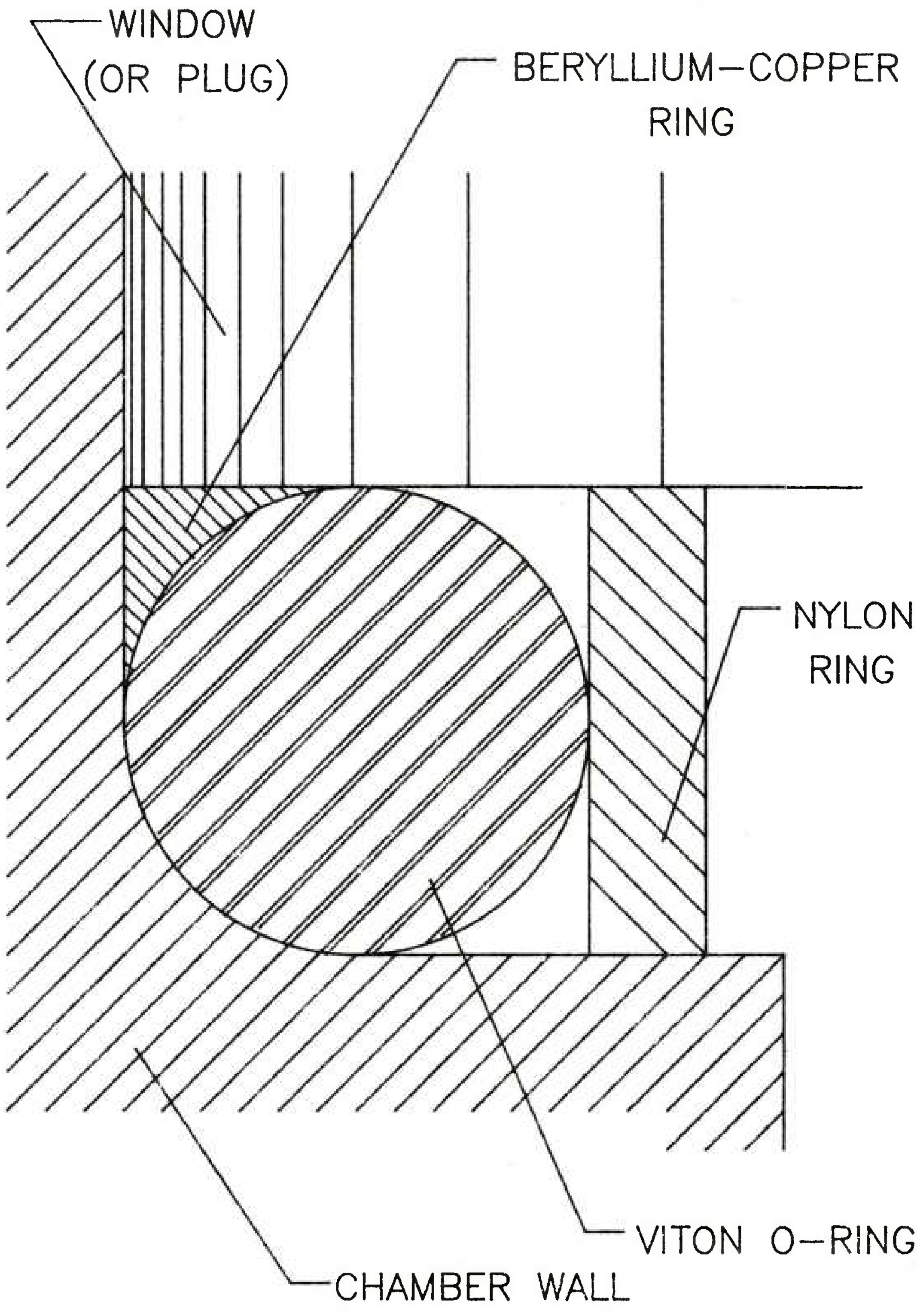

Figure 3. Sealing of the Combustion Chamber

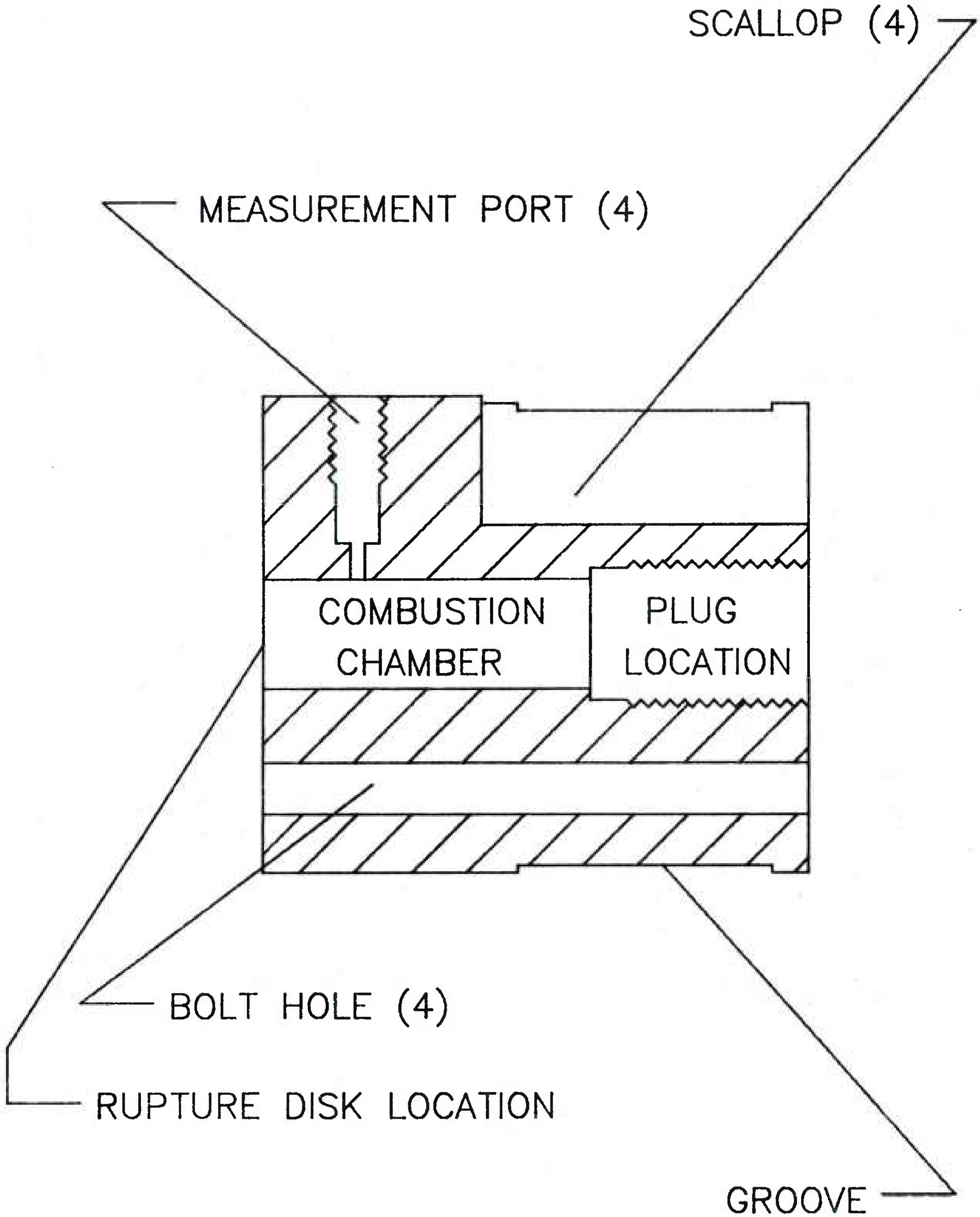

Figure 4. Schematic Drawing of the Combustion Chamber

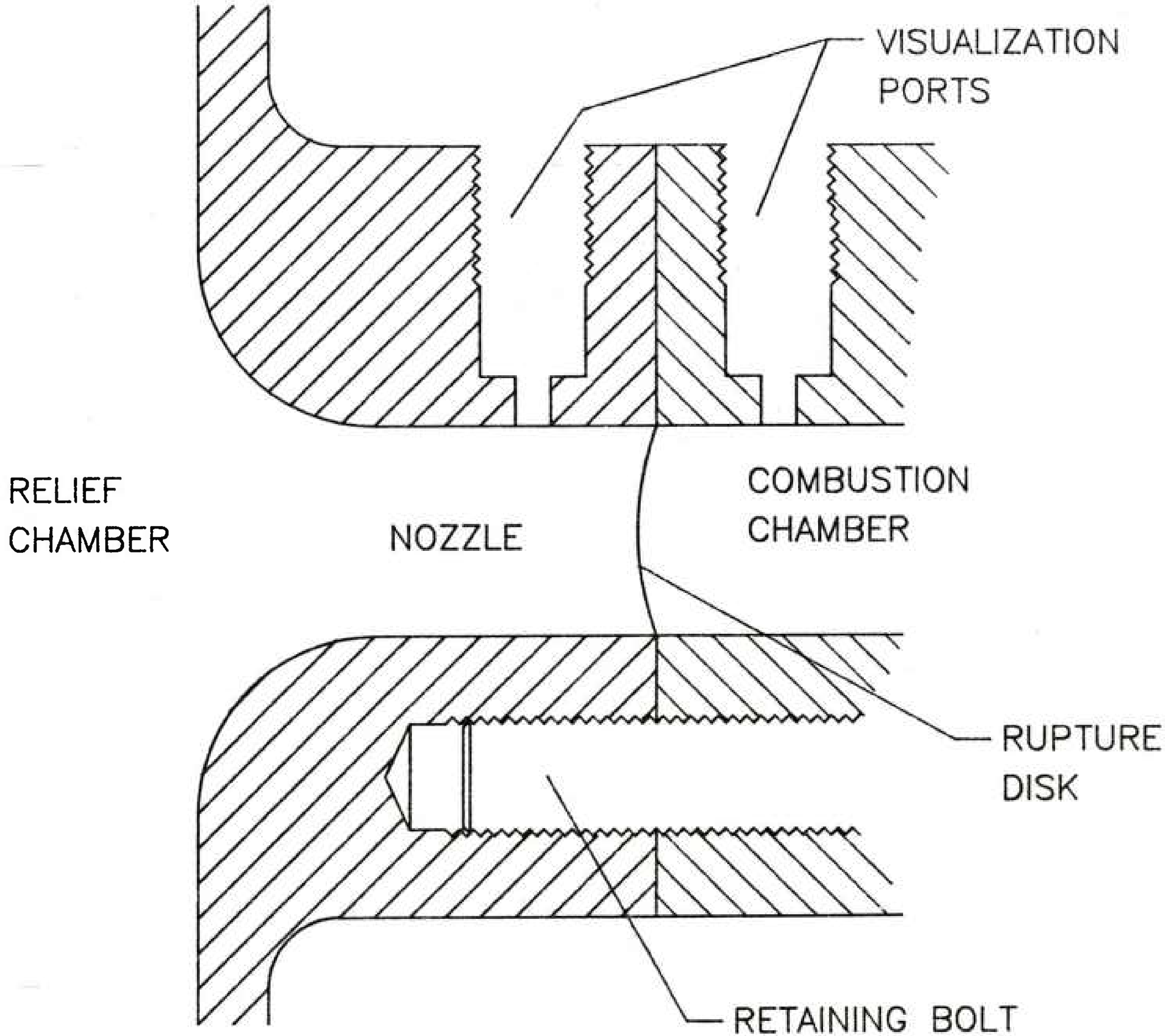

Figure 5. Relief Chamber Nozzle

experiment. The thin-wall pressure vessel formula yields a very small value for the wall thickness. But, since gas-sampling ports must be available along the chamber wall (and also a fitting for connecting a vacuum pump), the wall has a uniform thickness of 12.7 mm (0.5 in.), except of course in the portion that includes the nozzle previously described.

The gas-sampling ports are designed so fittings with a 1/4 NPT thread may be installed. Hence, they are only small cylindrical metal pieces that include a correctly threaded hole, and they are welded along the outside chamber wall. The mounting of the vacuum pump fitting results from a similar operation. A valve must be inserted between the vacuum pump and the chamber, and this valve is also used for venting of the gases after a firing.

In the current design, the relief chamber lid is held by 16 screws equally spaced around the chamber. But it has also been kept in mind that, in some cases, a quick opening of the chamber may be desired. Therefore, both the lid and the flange on the chamber exhibit tapered edges so a closing/opening system may eventually be designed. This system might consist of a crown, the inside shape of which would match these conical edges. This crown would be divided into two halves bound together by a hinge and a screw (Figure 6).

The MCDF is supported by a frame (not shown on Figure 1) through trunnions. This frame is classically made of angle iron. Because optical measurements are to be made with the MCDF, and because an accurate alignment of the windows with the laser beam may be required, the trunnions are designed so the MCDF axis may have any angular position with respect to their axis. The trunnions are welded along the diameter of a circular belt that fits into a groove machined in the outside chamber wall. The trunnions in turn fit into clamps located on the frame (Figure 7). Threaded holes are realized in the trunnions so screws may be used to hold the MCDF in any angular position.

The complete set of manufacturing drawings for the MCDF is reproduced in Appendix C.

III. OPERATIONAL PROCEDURE

The following procedure should be followed for a safe and efficient handling of the MCDF. First of all, the MCDF must of course be carefully cleaned after every experiment since combustion products will be deposited on the walls. The design has been conducted so as to make this operation easy.

The mounting of the pressure gages may be considered as a classical operation and therefore will not be the subject matter here. However, it is of an extreme importance to remember that the use of silicon grease for gage protection purposes (or in

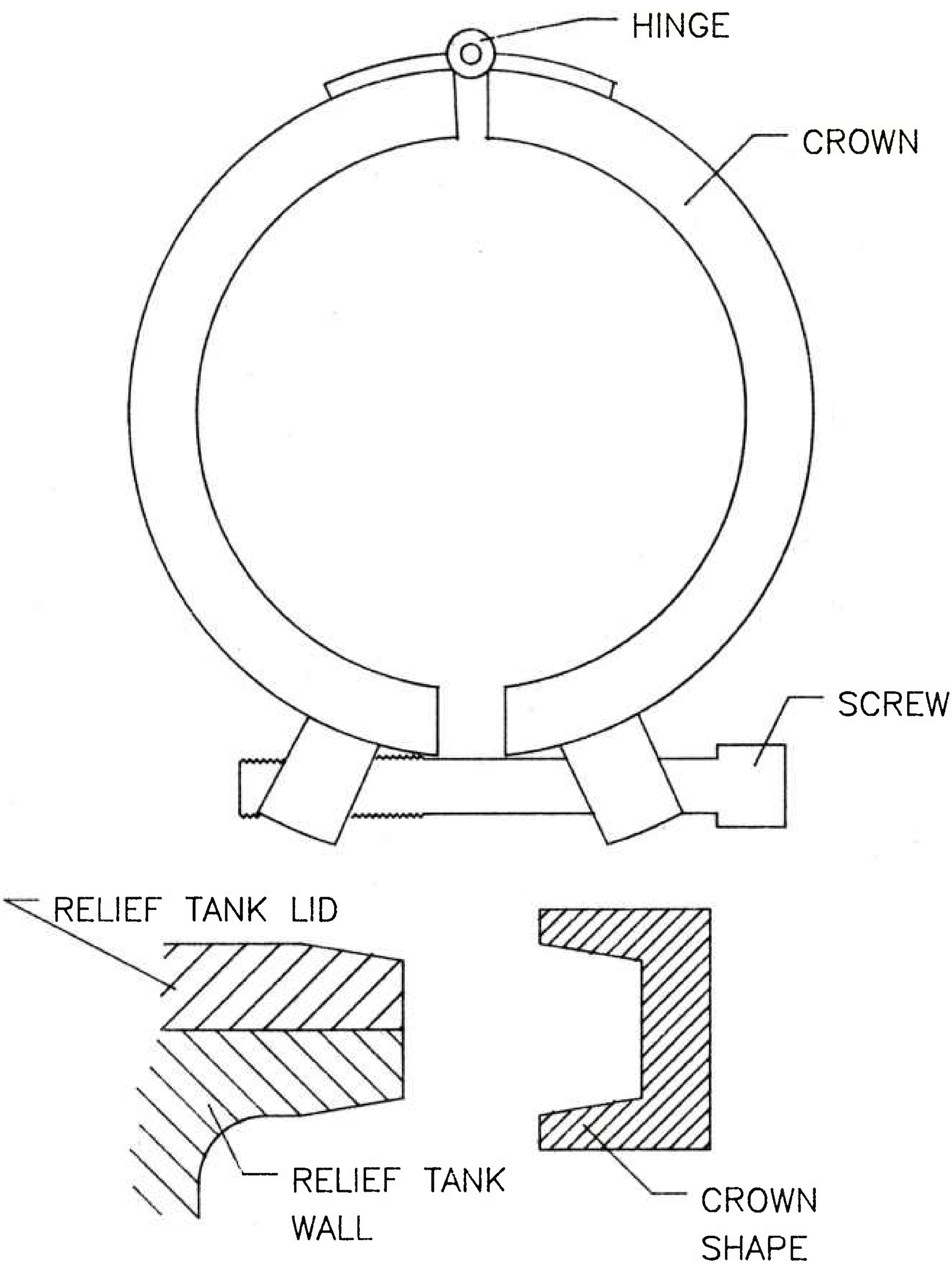

Figure 6. Quick Opening Device

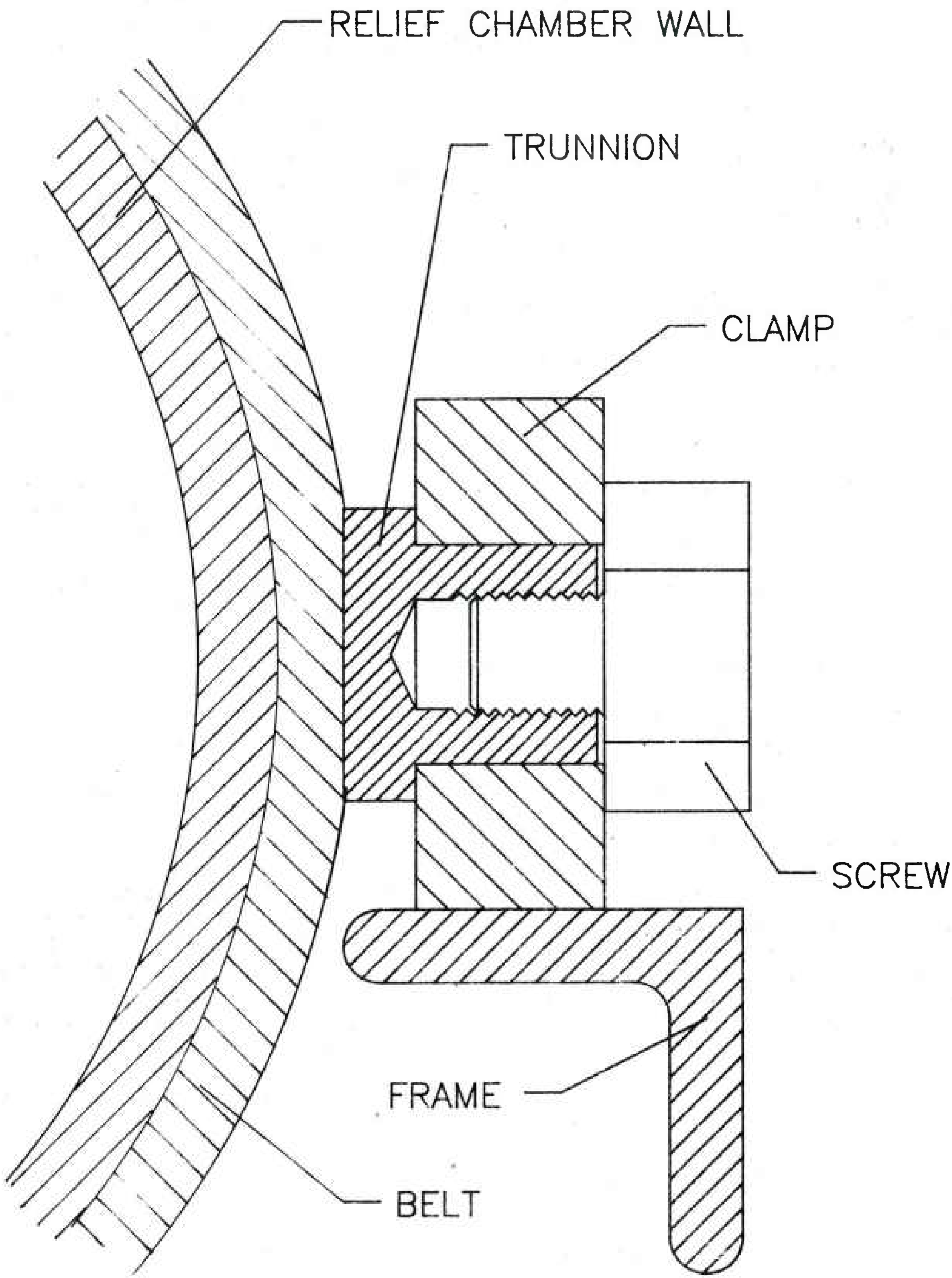

Figure 7. Trunnion Mount

connection with O-rings as will be seen later) must be limited to a minimum since the grease may release combustion products which would interfere with those produced by the propellant itself, and this situation is of course highly undesirable.

The mounting of the windows requires an extreme cleanliness of the visualization ports. This is an other reason why silicon grease must be used scarcely and even avoided if the first experiments made with the MCDF show that it is not absolutely necessary.

The loading of the MCDF is a very delicate operation which must be cautiously conducted. The safest configuration consists of placing first the propellant into the combustion chamber and only then installing the plug equipped with the ignition device. The procedure is then as follows:

1. Rotate the relief chamber around the trunnion so its axis is vertical and its nozzle is at the top.

2. Install the rupture disk in its housing; if the presence of a rupture disk is not required for some experiment, a previously blown disk may be used to improve the sealing.

3. Place the combustion chamber on top of the relief chamber and install and tighten the four retaining bolts.

4. Place the charge in the combustion chamber.

5. Install the plug equipped with the ignition device after the metallic O-ring has been placed in its groove.

6. Rotate the whole MCDF back to the desired position.

7. Connect the firing device to the firing line.

With respect to safety, these steps must be followed whenever possible. However, in some cases, this procedure may be harmful to the measurement quality. Indeed, if the propellant tested is composed of very small grains, some of these grains may enter visualization ports while the MCDF is upside down. Optical measurements would then be compromised. In such a situation, the procedure must be different from that described above:

1. Rotate the relief chamber so its axis is vertical and its nozzle is at the bottom.

2. Install the plug equipped with the ignition device on the combustion chamber.

3. Place the charge in the combustion chamber.

4. Place the rupture disk at the top of the combustion chamber and install the whole at the bottom of the relief chamber.

5. Install and tighten the retaining bolts.

6. Rotate the MCDF back to the desired position.

7. Connect the firing device to the firing line.

As it has been explained before, this may sometimes be the only applicable procedure, but ITS USE MUST BE STRICTLY LIMITED TO THE CASES WHERE IT IS ABSOLUTELY NECESSARY AND AN EXTREME CAUTION MUST BE OBSERVED DURING THE WHOLE PROCEDURE.

The next steps are the firing of the MCDF and the venting of the gases. These operations are usually remotely conducted, but the MCDF has been designed so it can resist pressures much higher than those that will be encountered during the experiments and therefore, and only if the measurements require it, the operator may stay in the same room as the MCDF when firing it. <u>However, the first testings of the MCDF are to be conducted either in an open-air range or in a blast chamber in order to insure that this is perfectly safe.</u>

IV. CONCLUSIONS

The fixture described in the preceding sections of this report is intended to provide phenomenological information on the early stage of the interior ballistic cycle. The data obtained should allow a better understanding of the ignition process and help the modelers to improve their theoretical predictions.

Charge designers should also find interest in the information collected by using the MCDF.

This fixture should therefore be intensively used in the future.

The major concerns that have guided this work were safety, universality of the fixture, and ease of operation.

The MCDF has been designed by taking into account a very high safety factor. This should make it very safe to use. However, preliminary testings must be carefully conducted in order to insure that the MCDF may be used in rooms that have not been designed to resist a blast.

As to the universality of the MCDF, it has been sought by using materials that allow the use of the fixture with various kinds of propellants, including liquid propellants which are known to be highly corrosive.

ACKNOWLEDGEMENTS

The author wishes to thank Dr. A. A. Juhasz who first proposed the idea for MCDF. Further thanks go to Dr. Juhasz and Dr. G. E. Keller for helpful discussions and providing the information that served as guidelines in the design of this fixture. In addition, the author is most grateful to Mr. W. F. Donovan who shared his technical expertise every time it was needed. Appreciation is also extended to the Societe Nationale des Poudres et Explosifs (France) and the Direction des Recherches Etudes et Techniques (France) for their support and assistance in making it possible for the author to work at the Ballistic Research Laboratory and to contribute to this project.

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[1] P. S. Gough, "Modeling of Rigidized Gun Propelling Charges," Ballistic Research Laboratory Contract Report No. ARBRL-CR-00518, November 1983, AD# A135860.

[2] T. C. Minor, "Characterization of Ignition Systems for Bagged Artillery Charges," 17th JANNAF Combustion Meeting, CPIA Publication 329, Vol. II, pp. 45-67, November 1980.

[3] T. C. Minor, "Experimental Studies of Multidimensional Two-Phase Flow Processes in Interior Ballistics," Ballistic Research Laboratory Memorandum Report No. ARBRL-MR-03248, April 1983, AD# A128034.

[4] R. E. Tompkins, Personal communication at BRL.

APPENDIX A

MECHANICAL PROPERTIES OF INCONEL ALLOY 718

Inconel alloy 718 is a non-ferrous alloy, the average composition of which is given in Table A-1.

TABLE A-1. COMPOSITION OF INCONEL ALLOY 718

Element	Percent
Chromium	19
Iron	17
Cobalt	5
Molybdenum	3
Titanium	0.8
Aluminum	0.6
Nickel	Balance

Annealing and aging considerably strengthen this alloy. For a hot rolled bar, the mechanical properties resulting from a given heat treatment are shown in Table A-2.

TABLE A-2. MECHANICAL PROPERTIES OF A HOT ROLLED BAR

Heat treatment	Anneal + Age
Condition	1800F, 1 hr +1325F, 8 hr*
Ultimate stress, ksi	201
Yield stress, ksi	171
Elongation, percent	26
Reduced area, percent	50
Hardness, R_c	41

* Furnace cool 100F per hour to 1150F, hold 8 hr, AC

With these values, it is possible to calculate the thickness of the wall chamber by using the classical thin wall pressure vessel formula:

$$\sigma_{max} = p \frac{b^2 + a^2}{b^2 - a^2} \tag{A-1}$$

where: σ_{max} is the maximum value of the hoop stress,
p is the pressure inside the vessel,
a is the inside diameter,
b is the outside diameter.

It must be noted that Eq.(A-1) gives the value of the stress, considered uniform, in a thin wall and the maximum value of the hoop stress in a thick wall, i.e. on the inside wall.

The application of Eq.(A-1) to the following values:

p= 50 kpsi ; σ_{max}= 171 kpsi ; a= 1.5 in.

yields 2 in. for the outside diameter, which gives a wall thickness value of 0.25 in. (6.35 mm).

APPENDIX B

CHOICE OF THE RUPTURE DISK

The Fike Metal Products Corporation manufactures rupture disks in a number of shapes, sizes and materials. The choice of the rupture disk used in the MCDF has been oriented by a few basic requirements.

First of all, the fragmentation of the disk should be avoided in order to protect the walls from impacts after the rupture of the disk. For this reason, the disk is scored on the low pressure side.

The conventional Fike disks include a 30-degree seat which would occupy too much space to permit the windows to be as close to the disk as desired. Therefore, the seat of the selected disk is flat. But because of the relatively high pressures involved, a ring is welded on the high pressure side of the seat. This ring fits into a groove machined in the combustion chamber wall. The purpose of this ring is to prevent the extrusion of the disk at the seat area, extrusion which would be possible at high pressures because the seat is flat.

A sketch of the disk shape and mounting is shown in Figure B-1.

Because of its mechanical properties as well as because of its good resistance to severe environments, the material selected for the disk is Nickel.

Various disk sizes are to be ordered so the burst pressure may range from 3.5 MPa (500 psi) to 35 MPa (5000 psi).

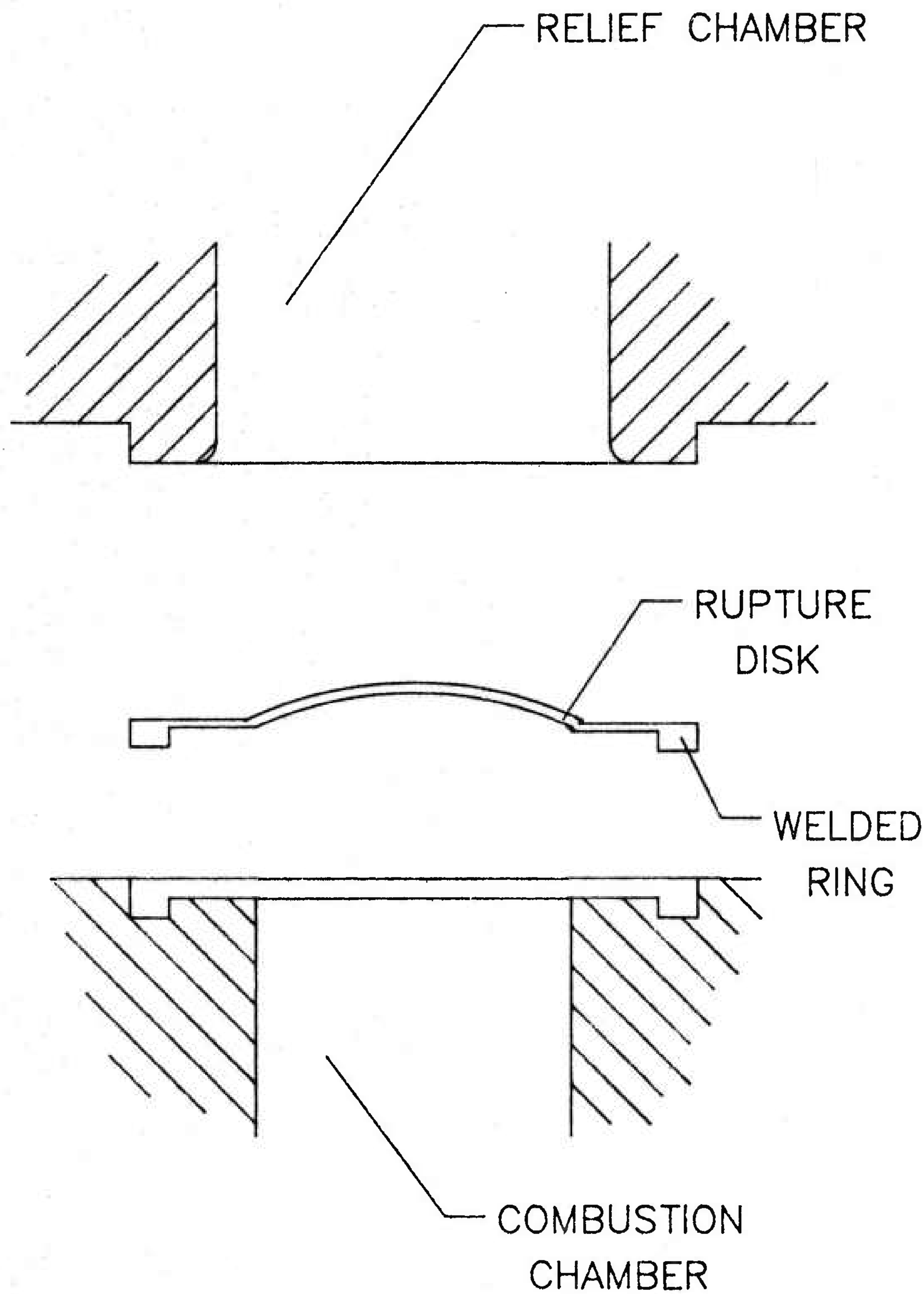
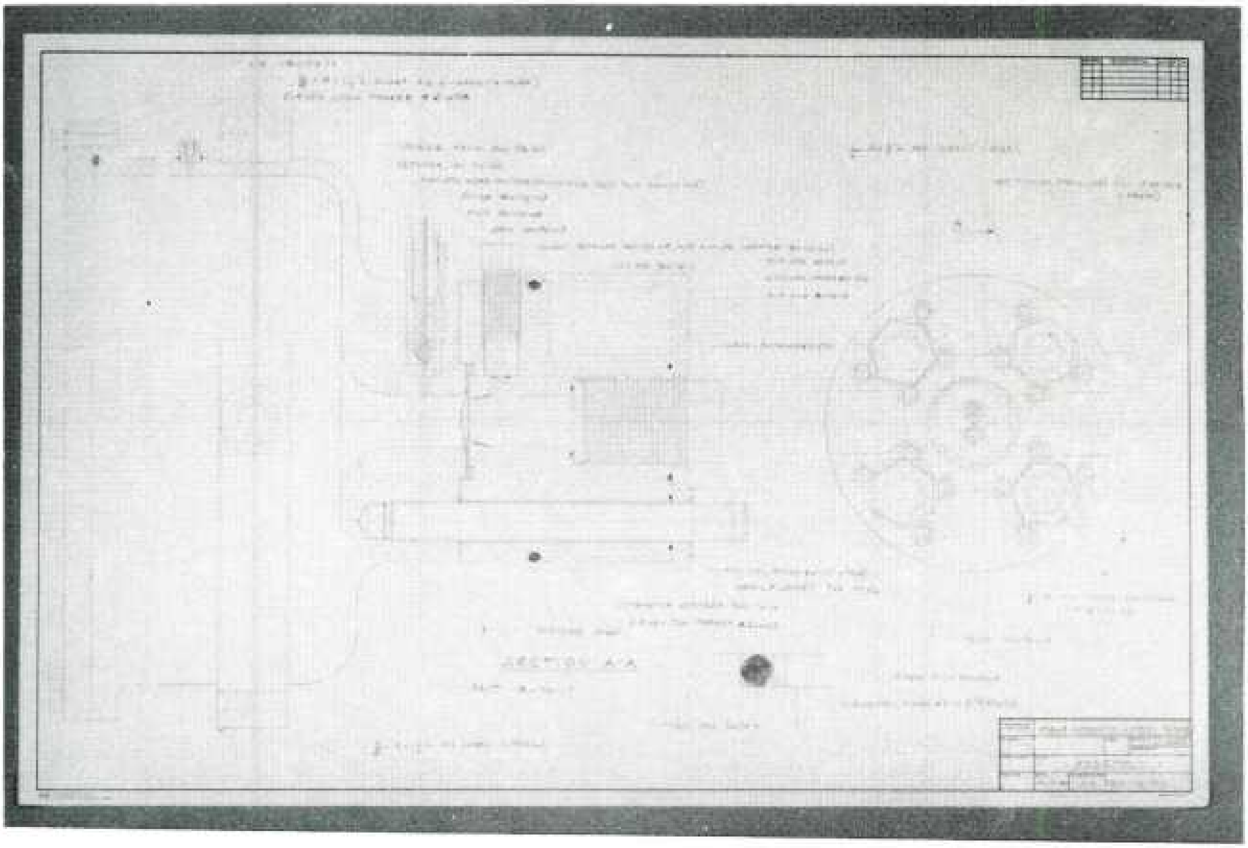


Figure B-1. Rupture Disk Mounting.

APPENDIX C

MANUFACTURING DRAWINGS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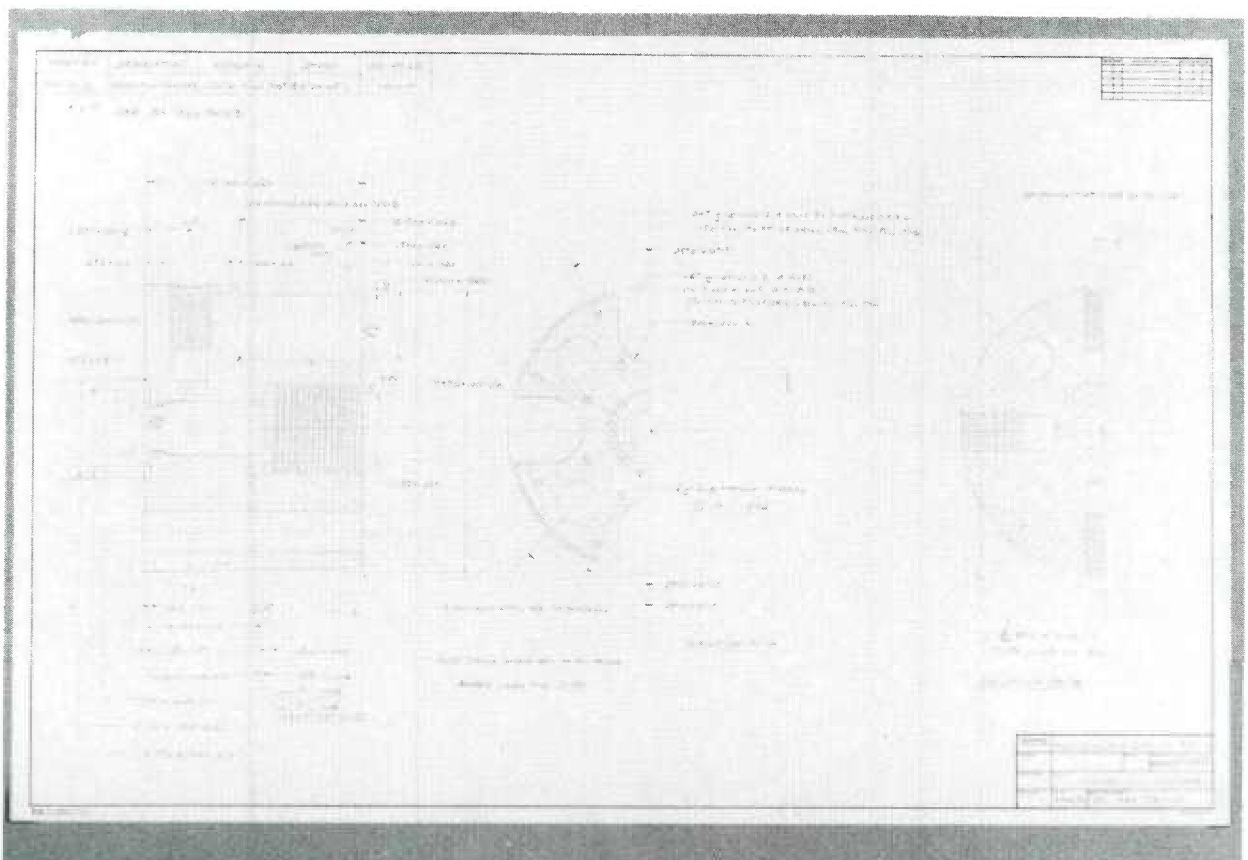

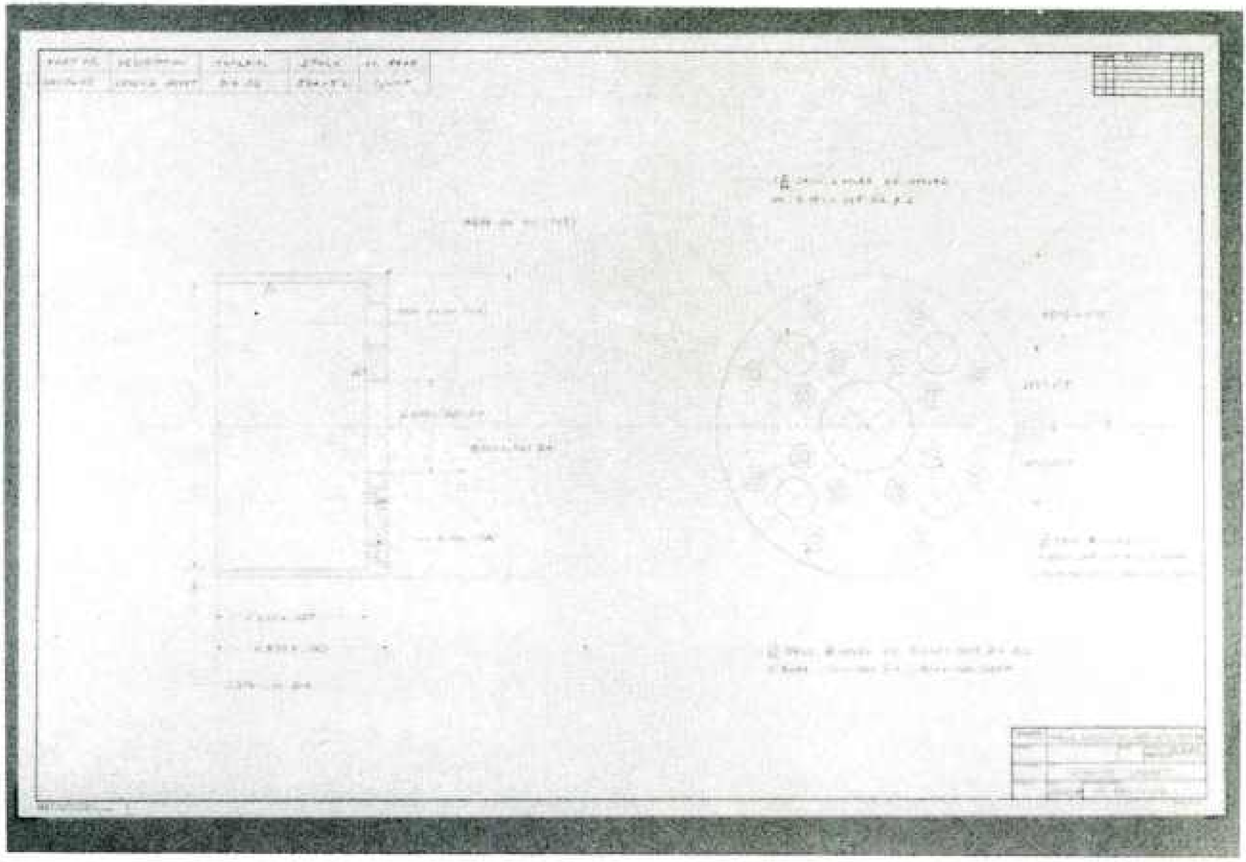

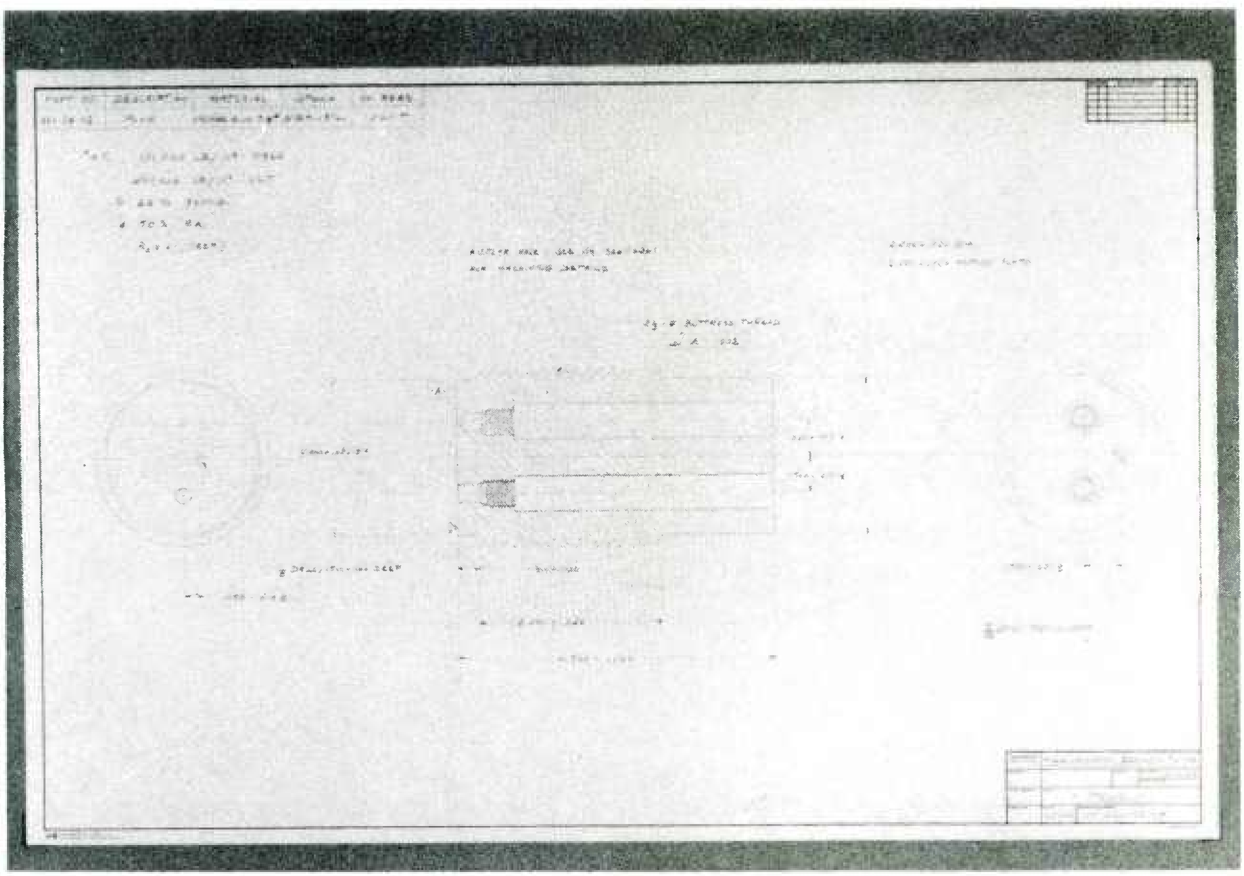

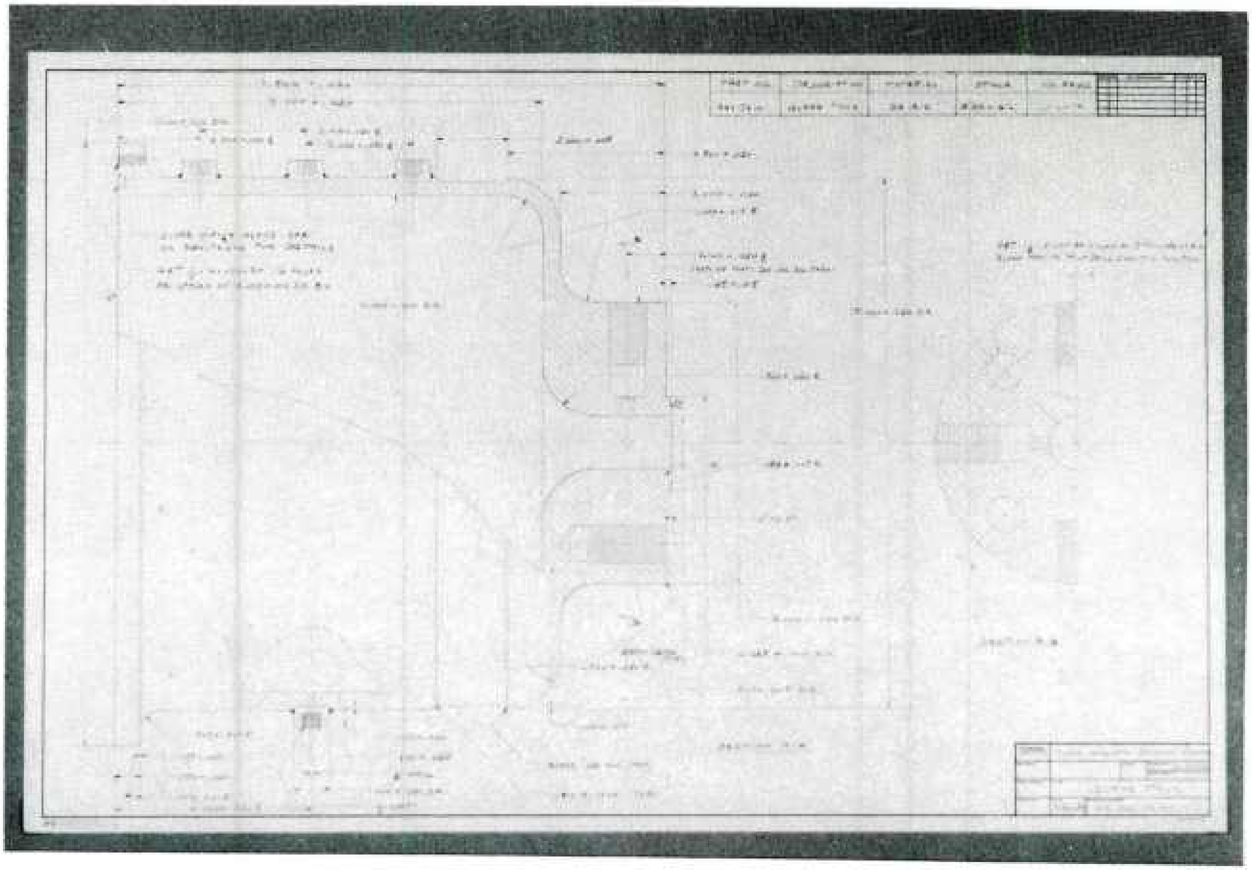

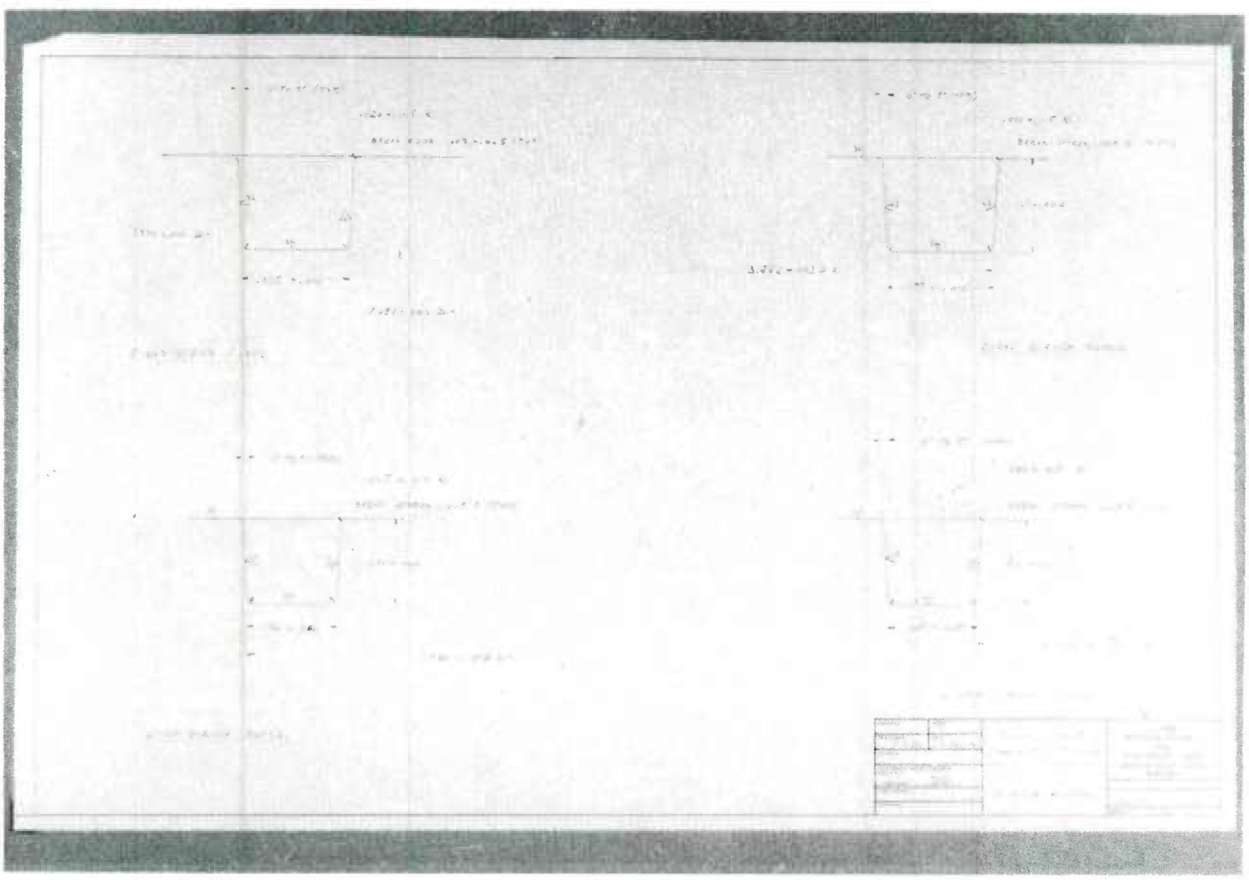

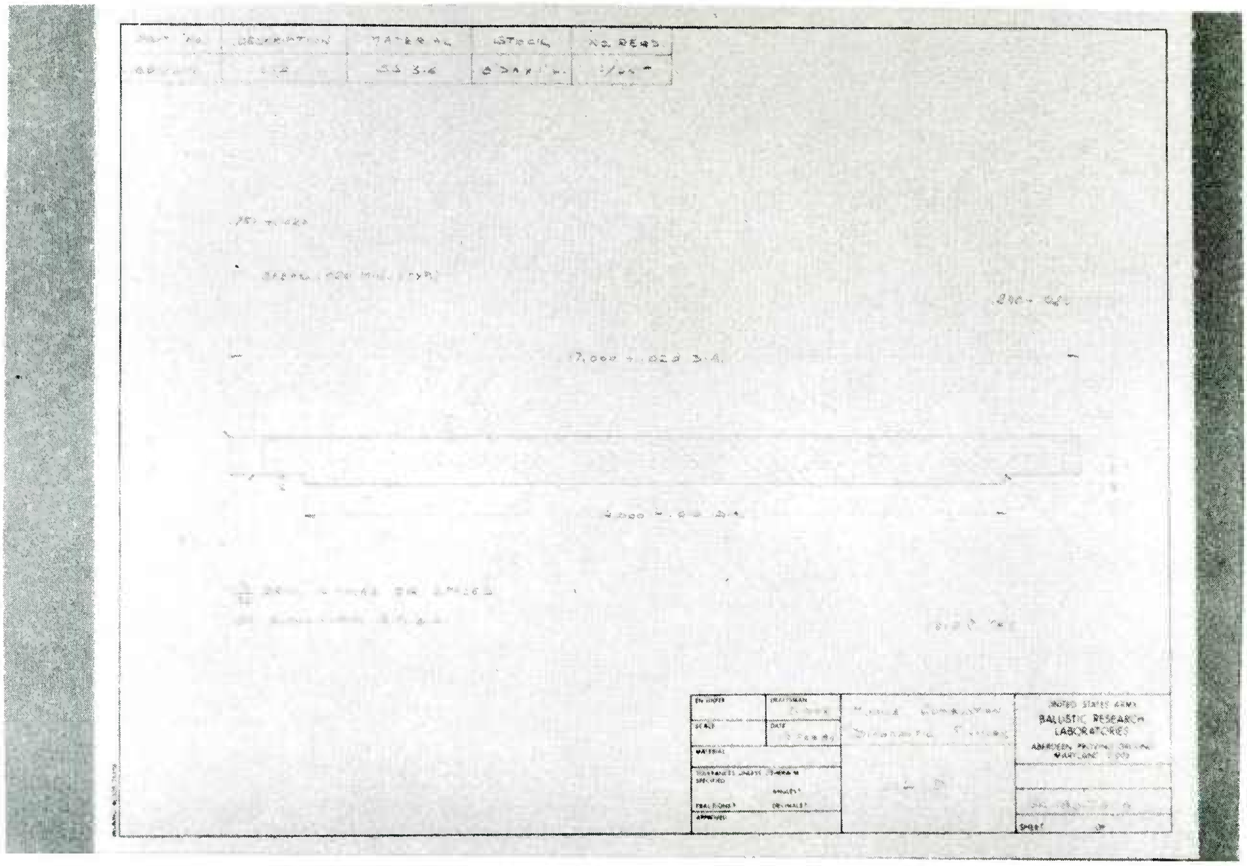
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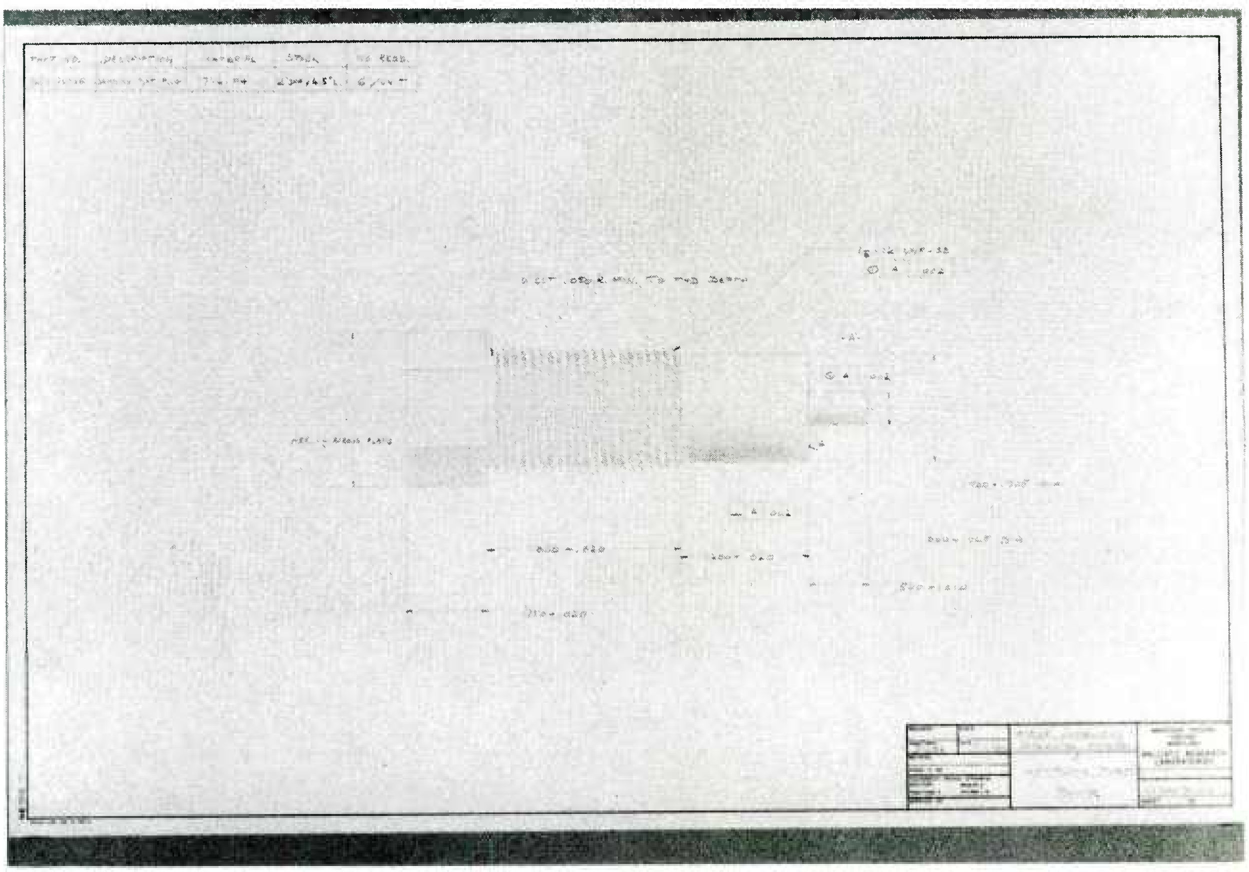

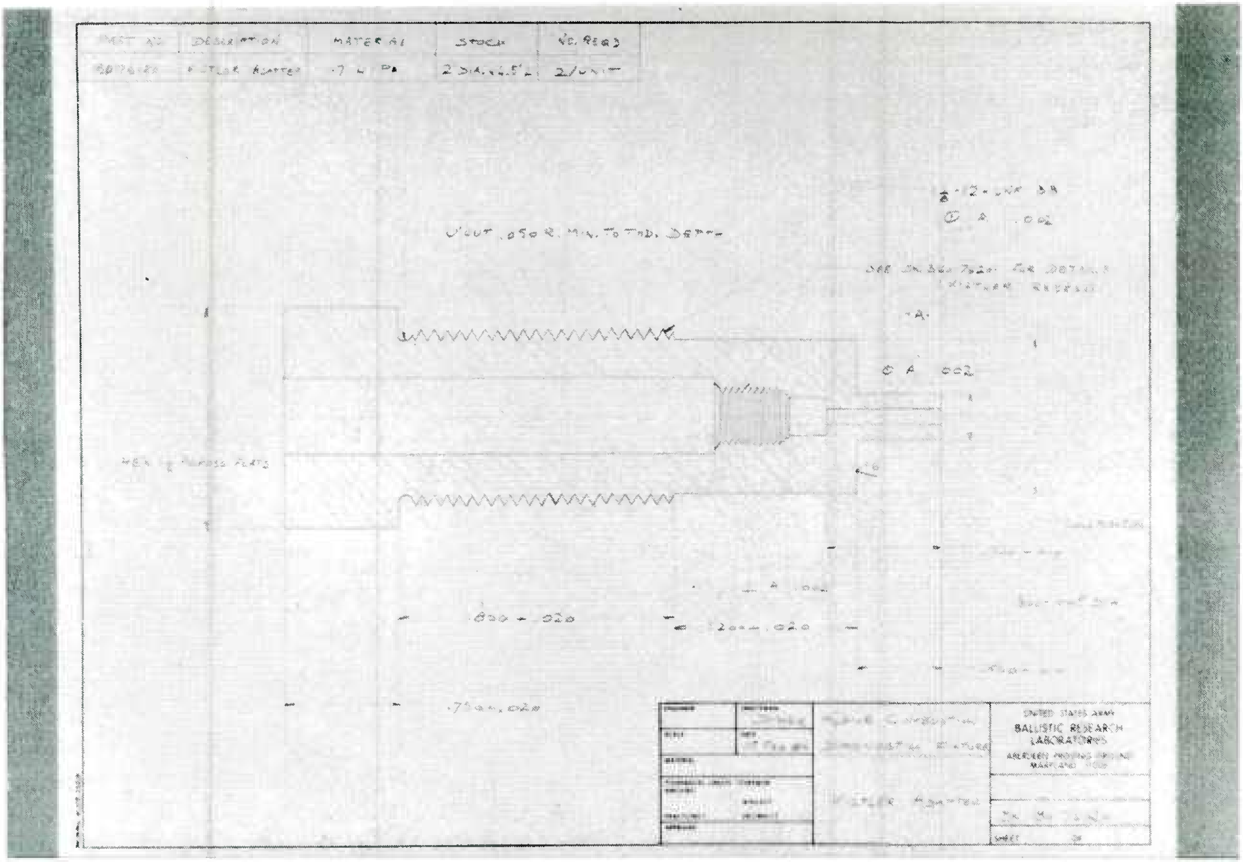
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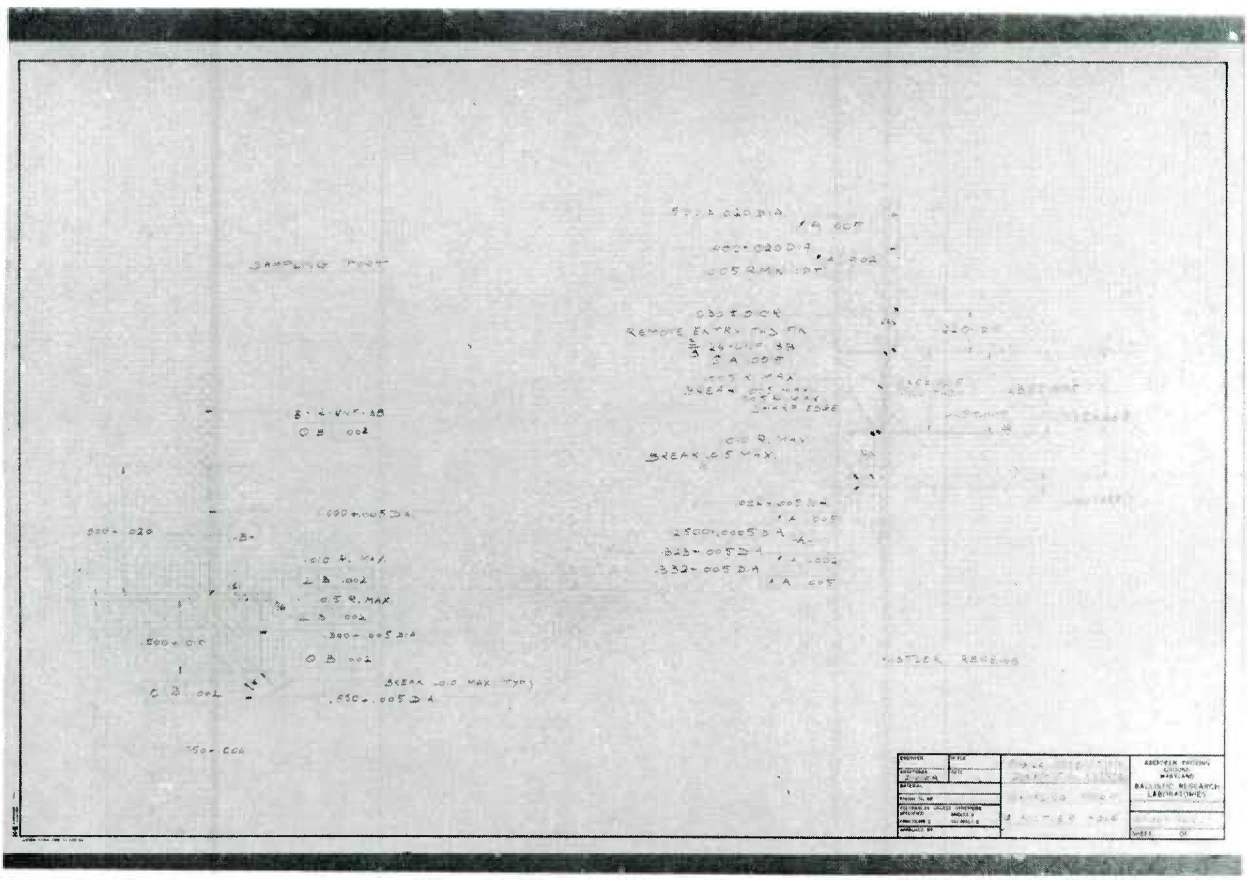
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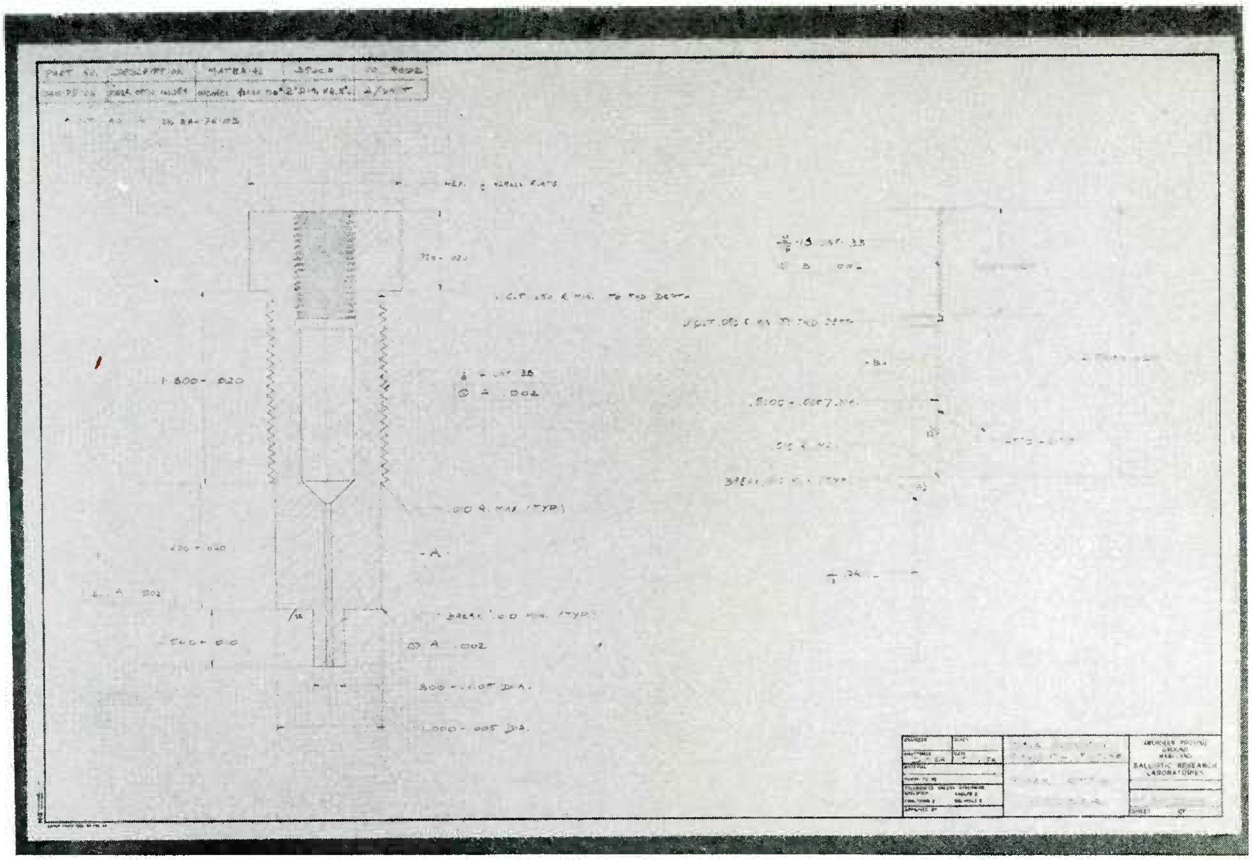

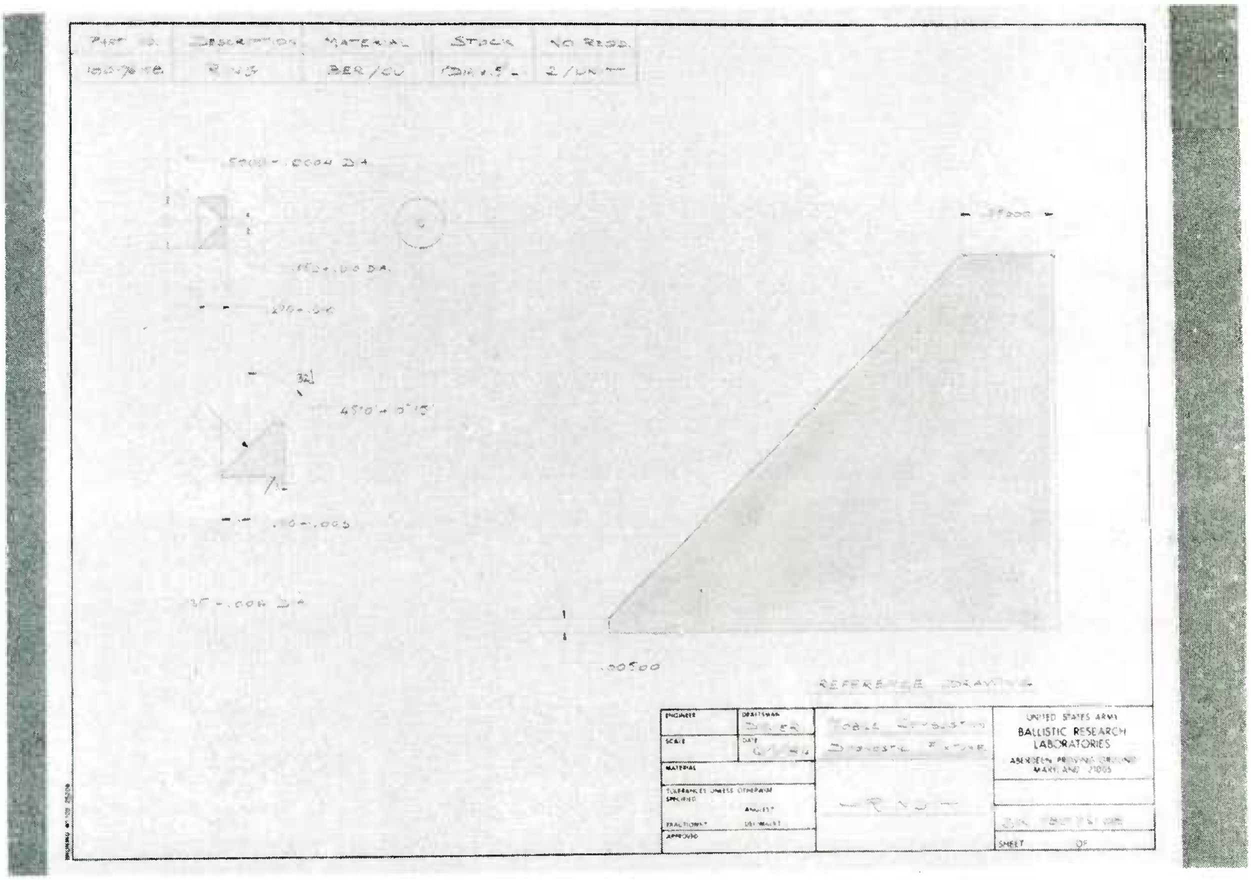
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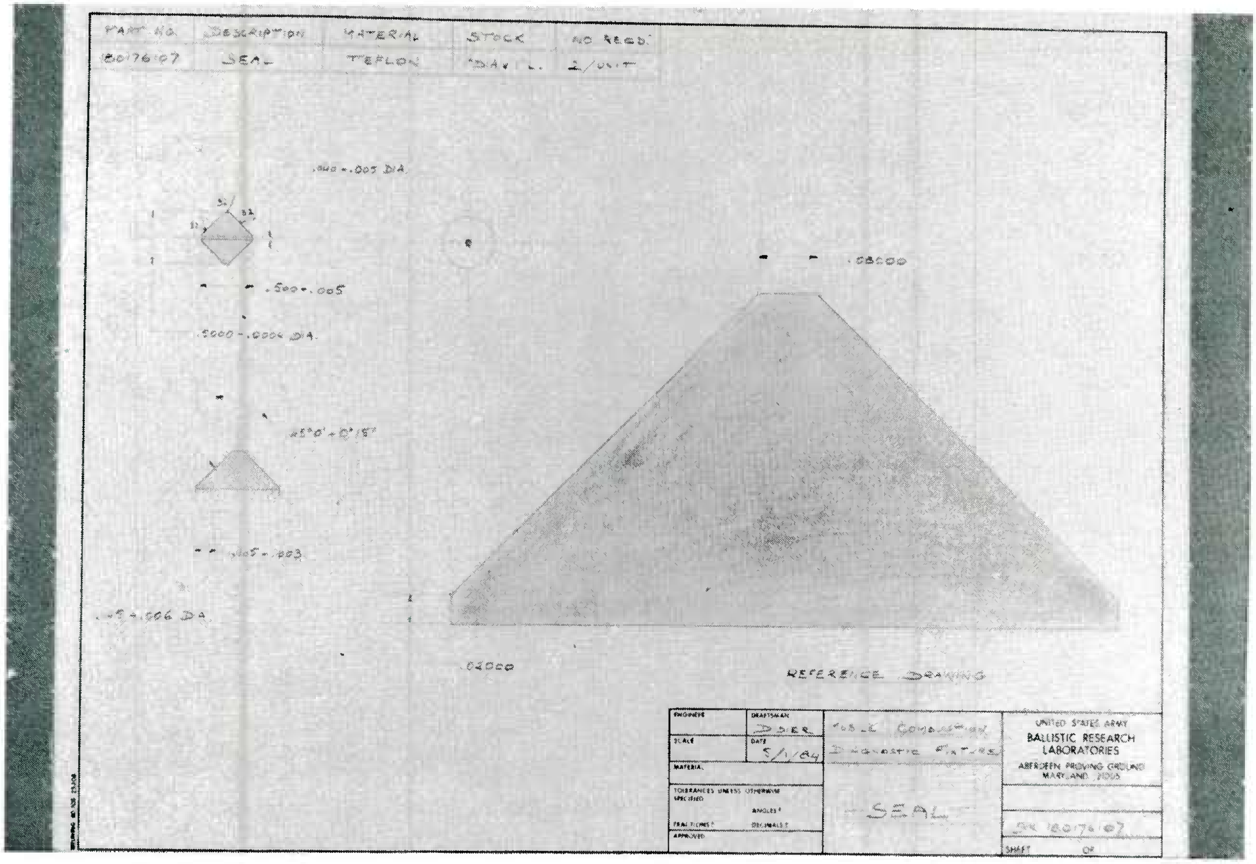
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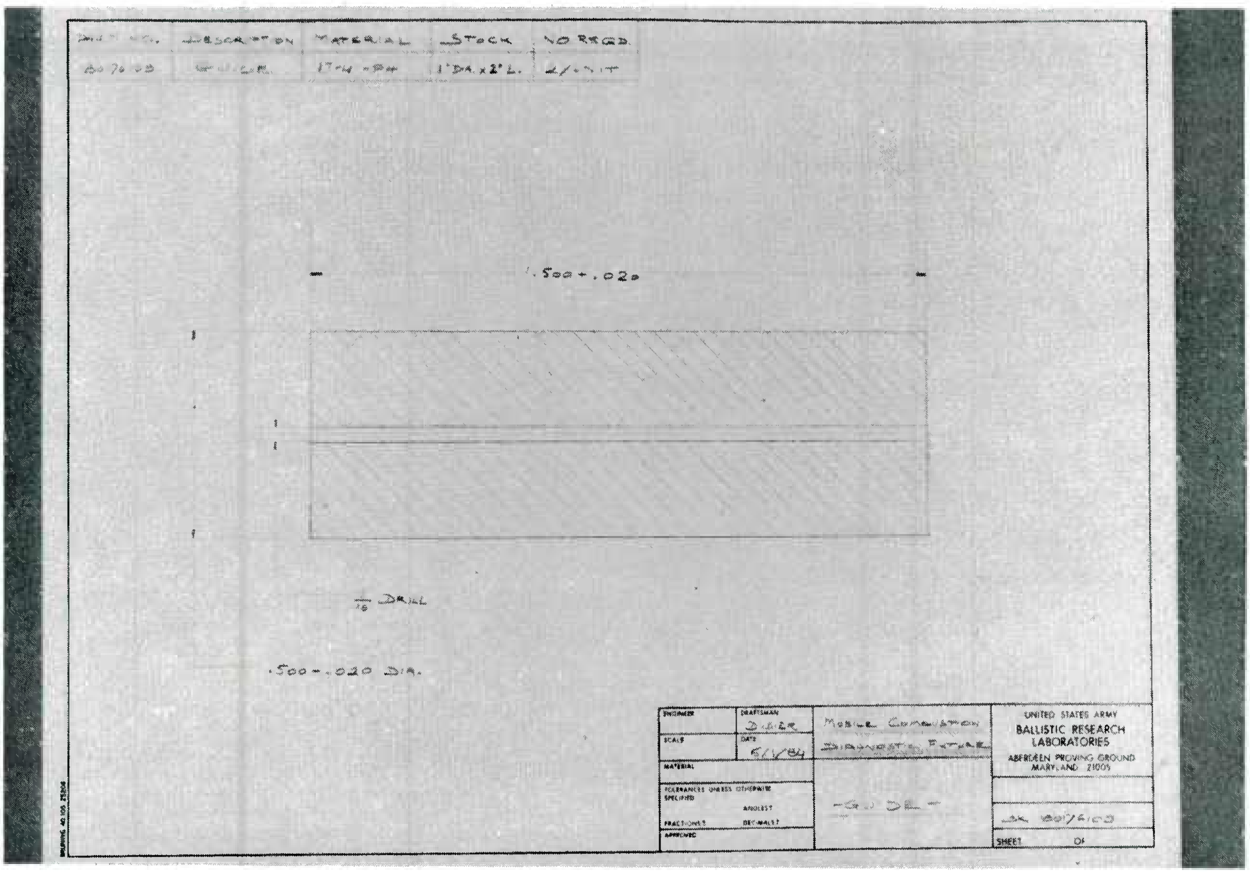
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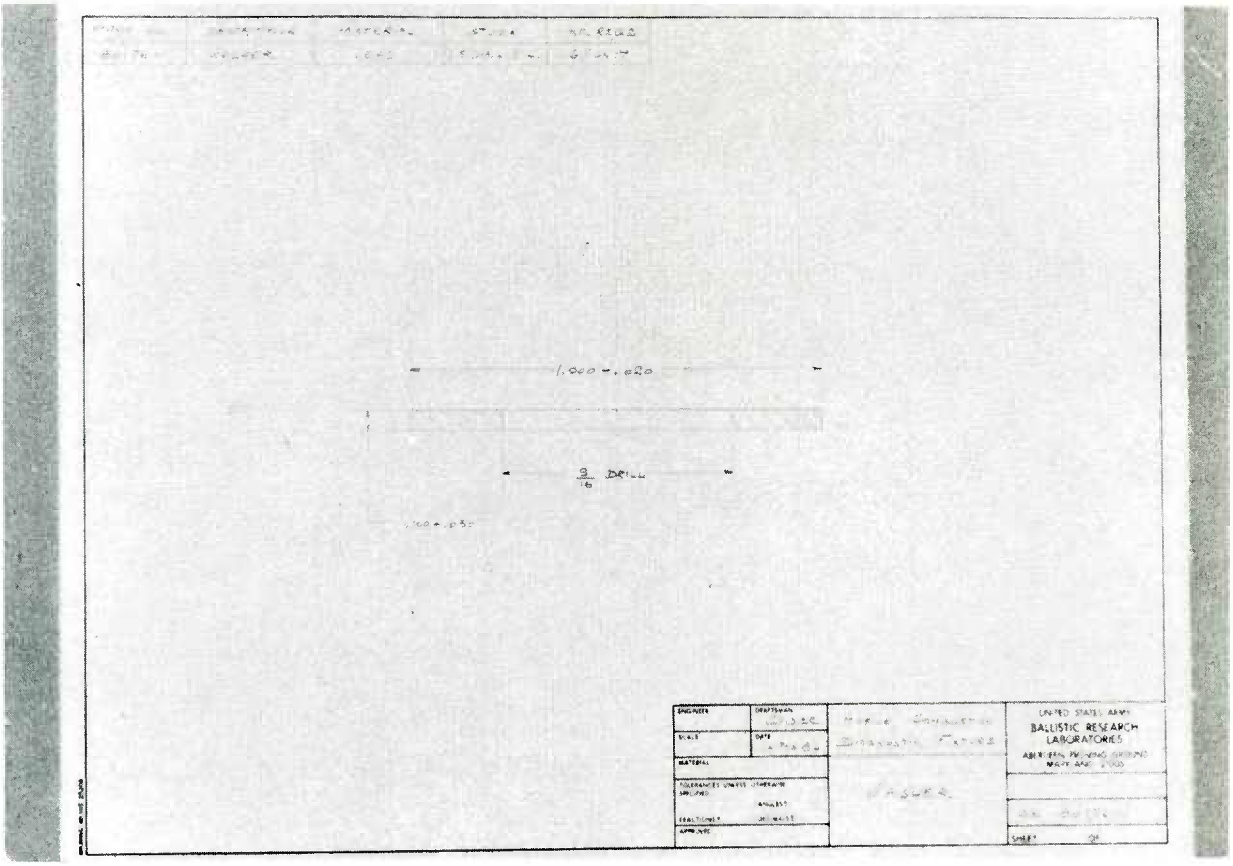
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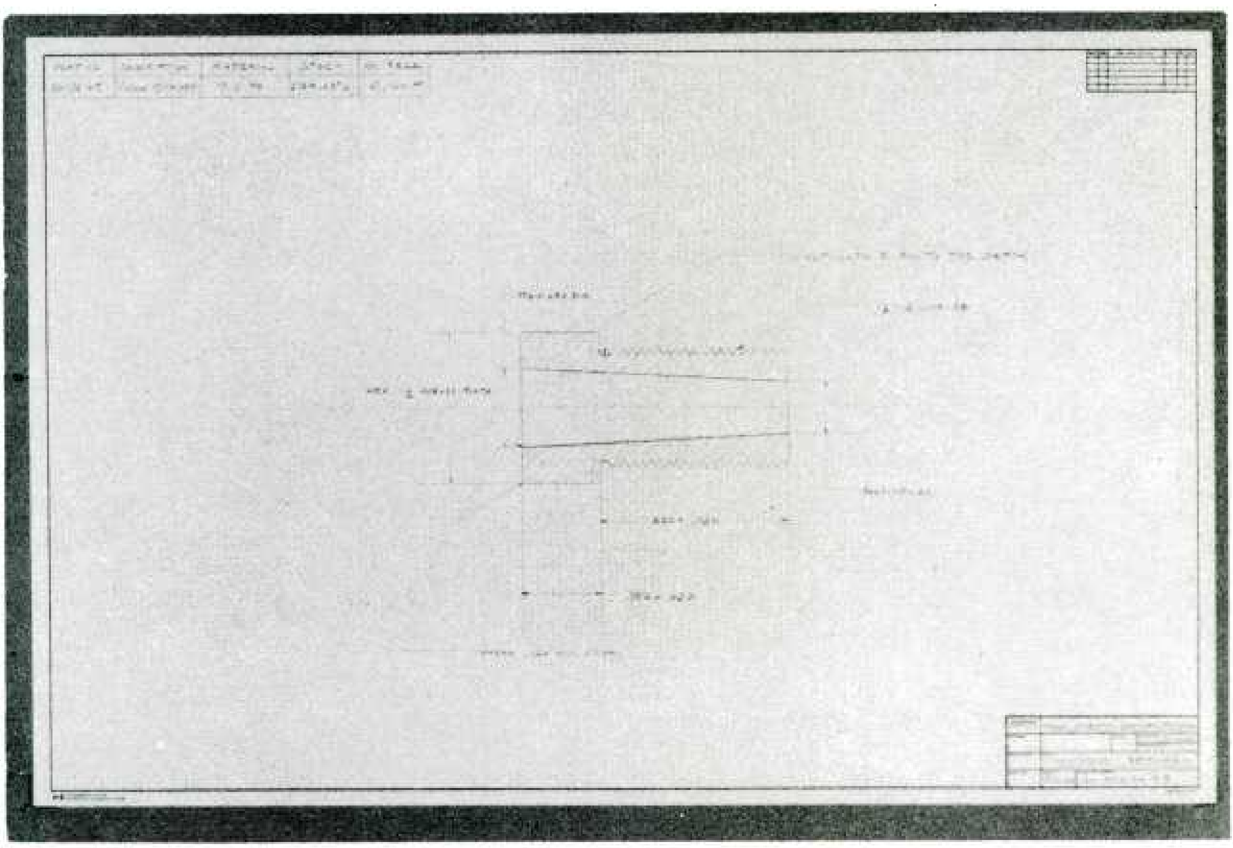

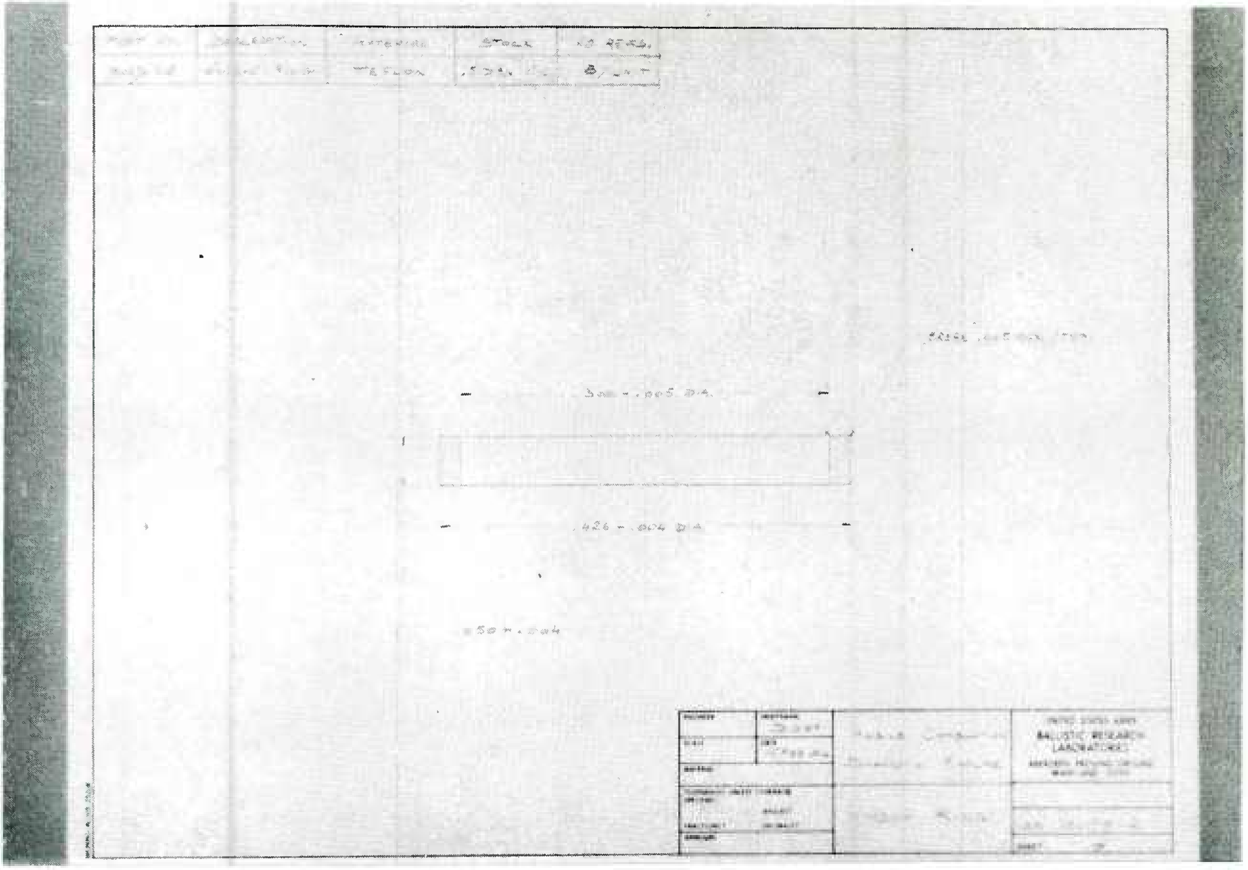
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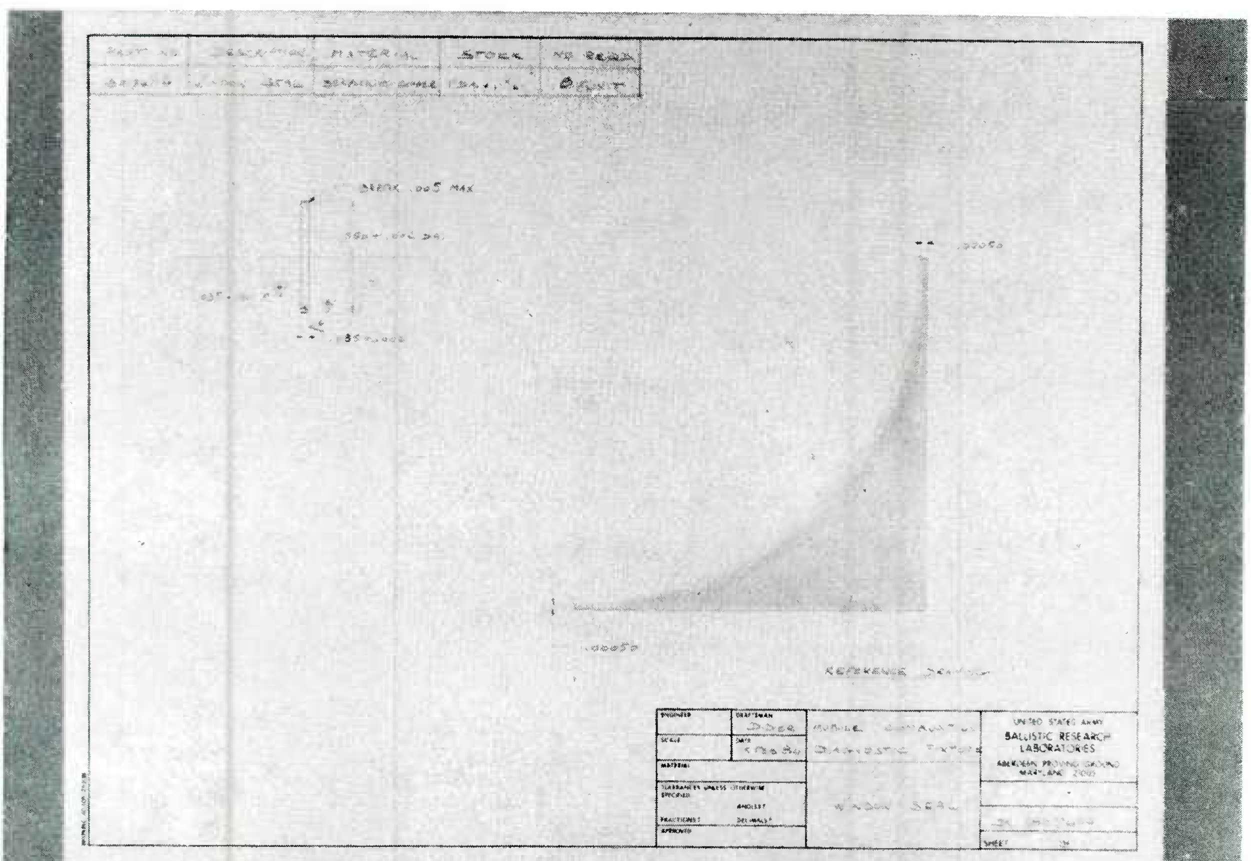
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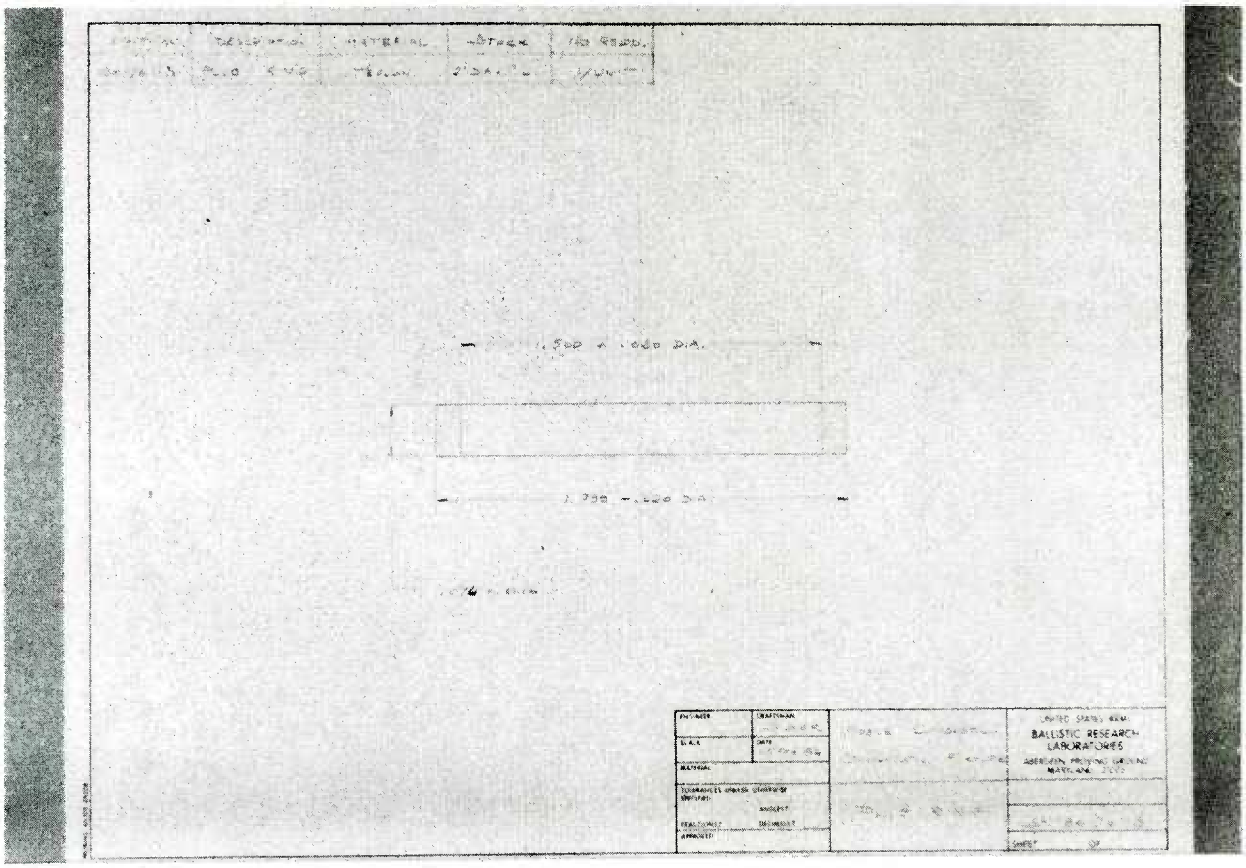
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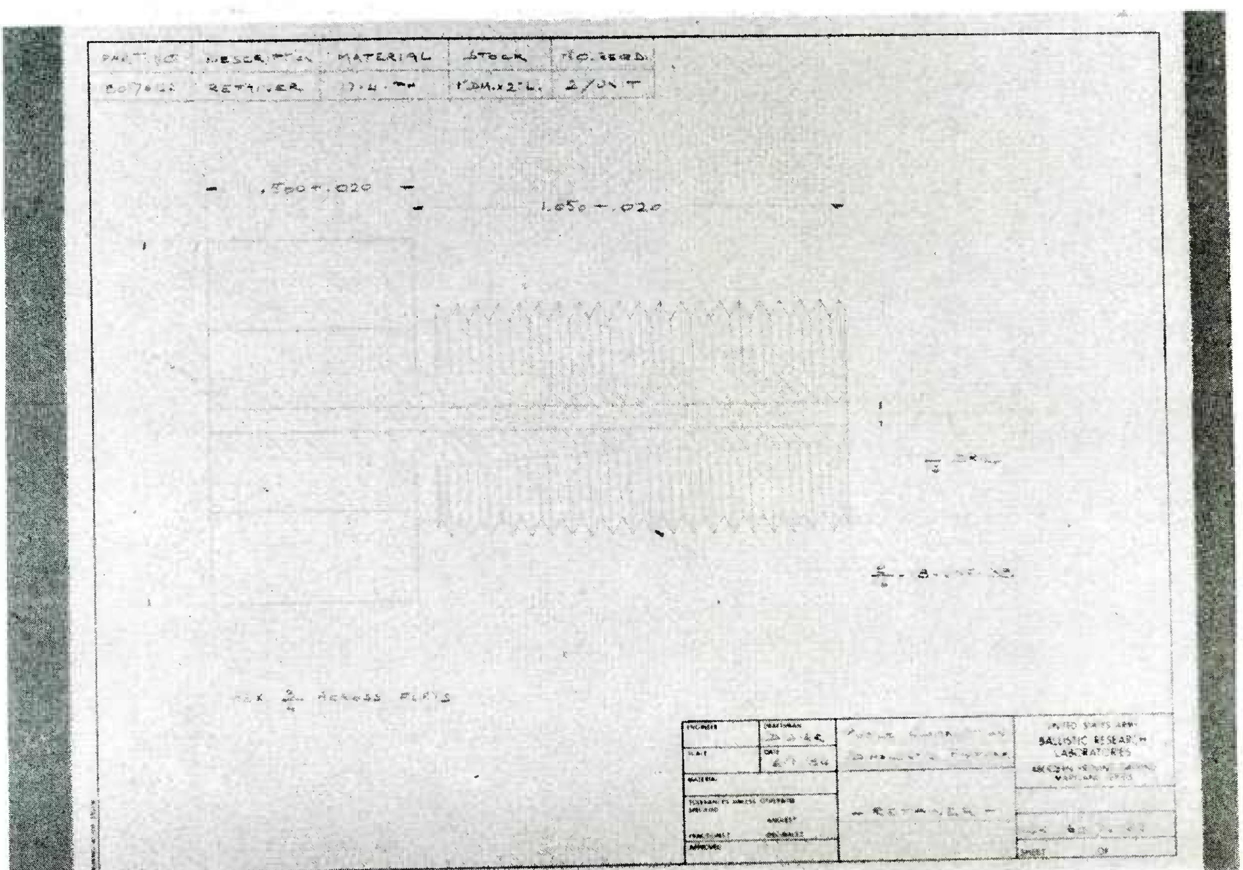
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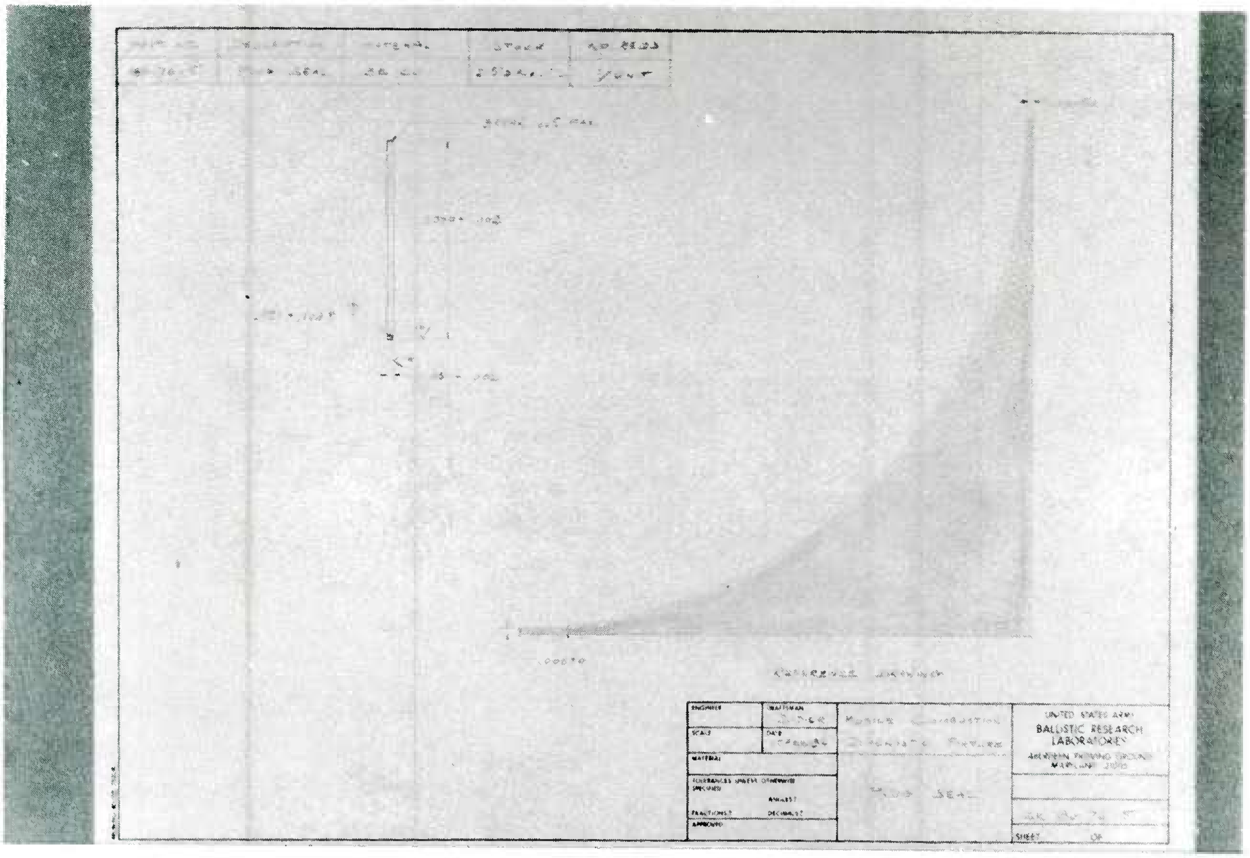

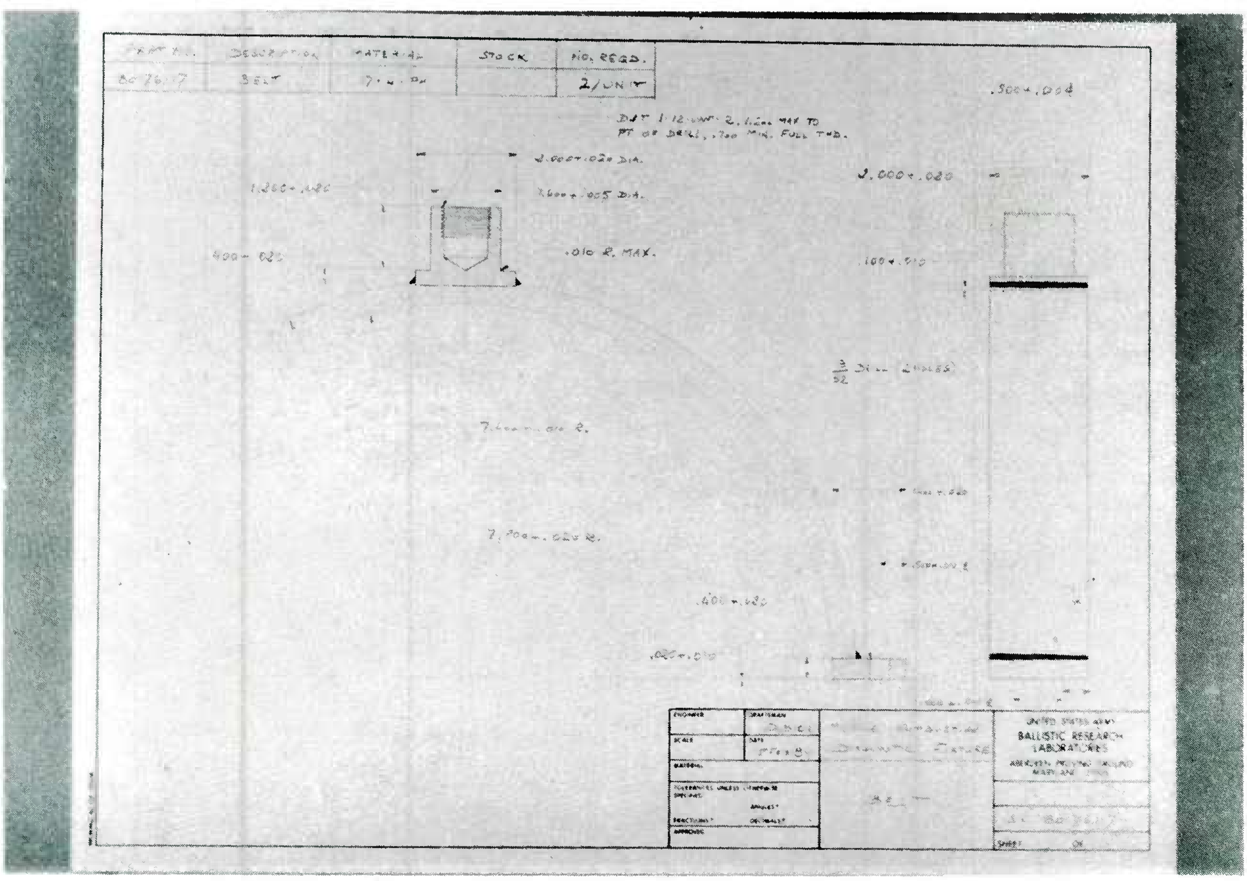

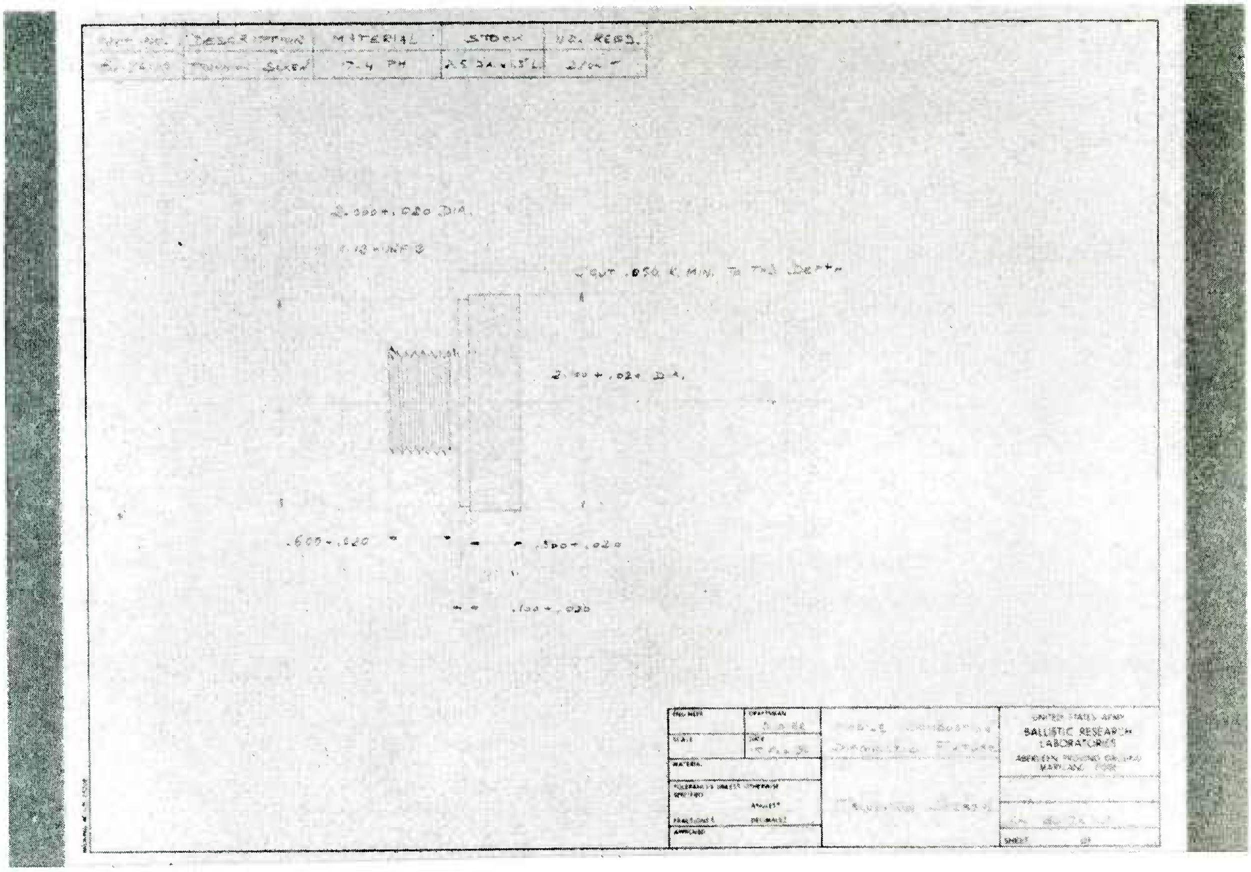
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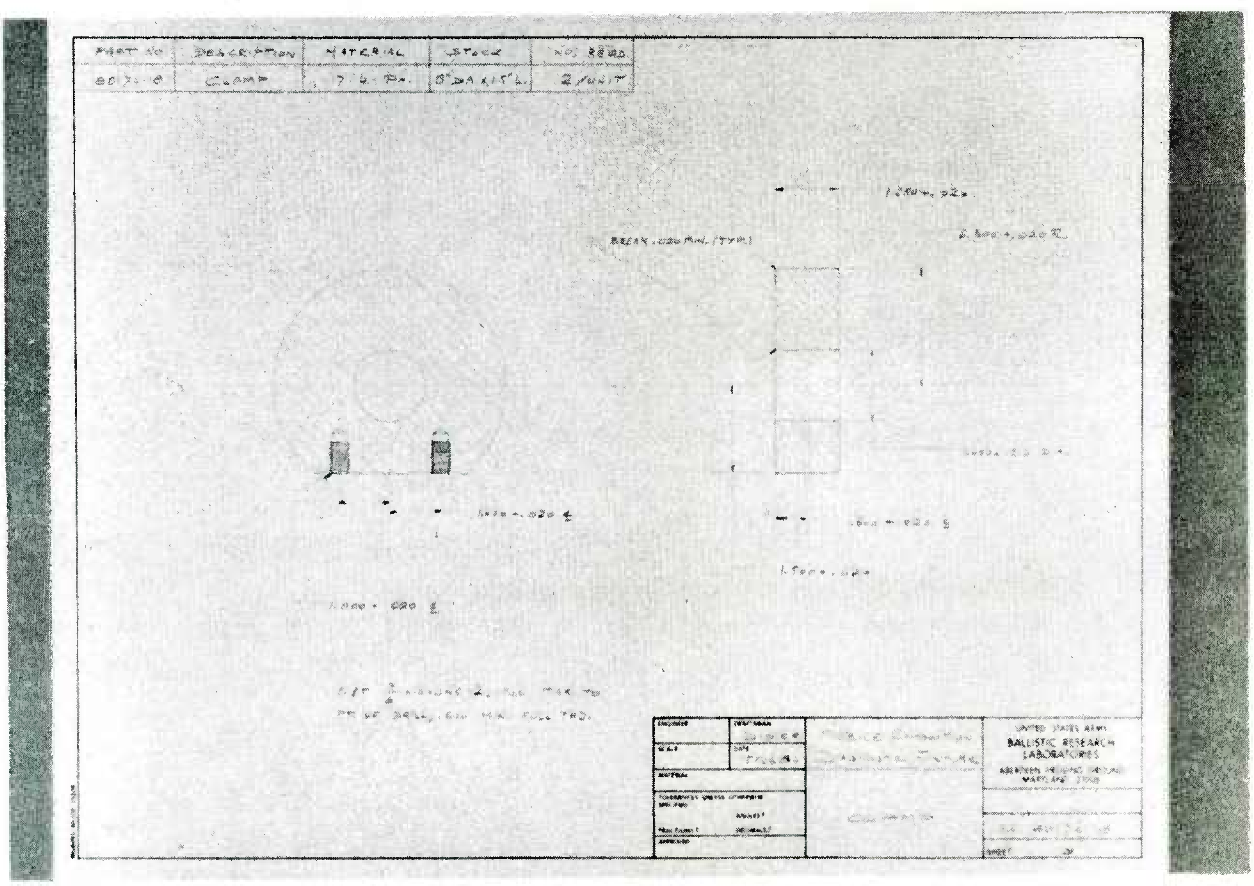
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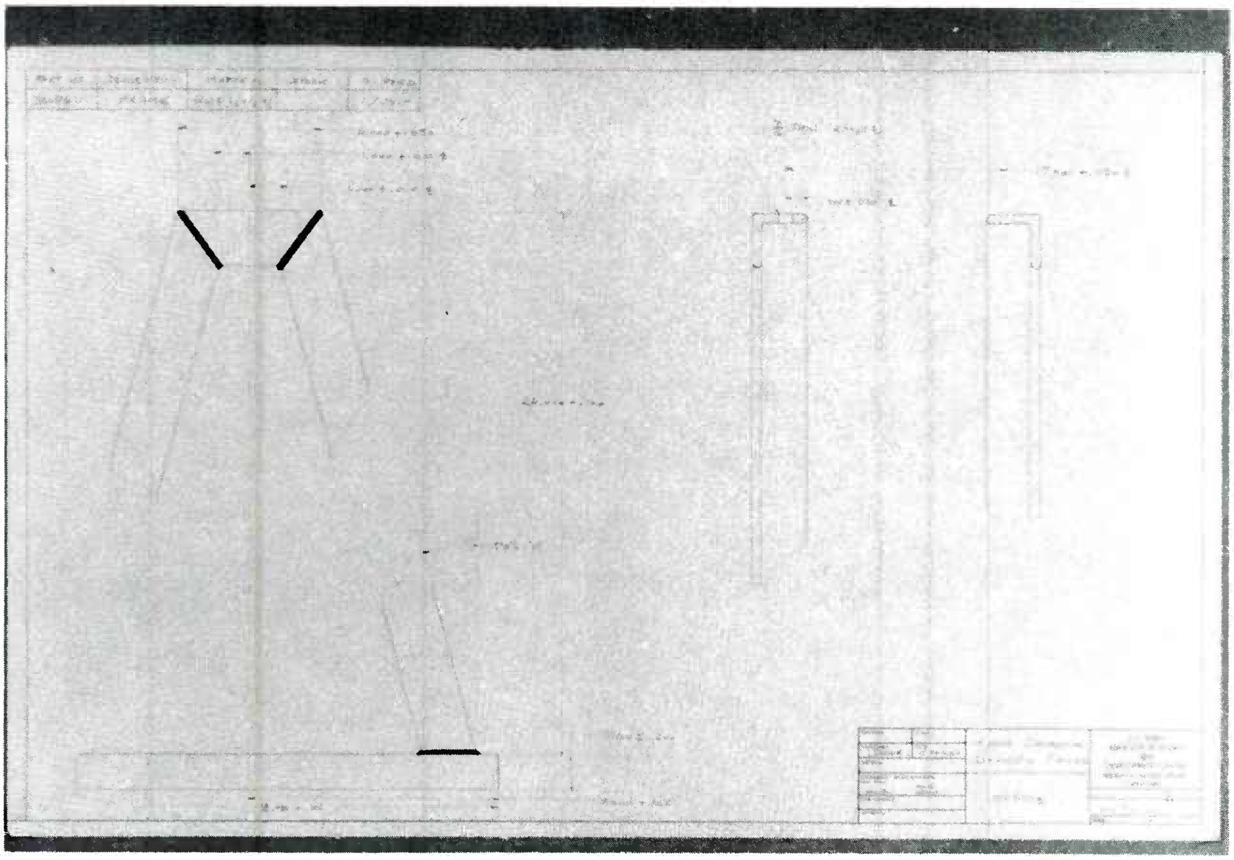

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